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TITLE: Pathomechanics of Post-Traumatic OA Development in the Military Following Articular Fracture

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14. ABSTRACT
The objective of this research is to develop new models for predicting the risk of post-traumatic osteoarthritis (PTOA) following intra-articular fracture (IAF). We have analyzed pre- and post-treatment CT data from patients with combat-related IAFs to measure fracture severity and post-reduction contact stress exposure. Our partner at SAMMC continues screening the DoDTR to identify and enroll subjects. The imaging data for 57 subjects with collectively 95 fractures have been forwarded to us for analysis, and we have completed fracture severity analysis of 71 IAFs. This is in addition to fracture energies having now been computed for 226 civilian IAFs. In a preliminary analysis of our military data, we found that fracture energy can predict painful and activity-limiting PTOA, which contributes to late amputation in military blast injuries. Twenty military subjects with tibial pilon IAFs resulting from blast injuries were studied. Of the 15 subjects with sufficient follow-up data, 5 limbs were amputated. There was a statistically significant difference in the fracture energies of the amputation and retained limb groups (17.4 vs 6.6 J, respectively; $p=0.0059$). An objective fracture severity score nearly perfectly predicted amputation. During the coming year, we will be performing additional analysis of fracture severity in more cases to further test these findings

15. SUBJECT TERMS
post-traumatic osteoarthritis, CT-based analysis, intra-articular fractures

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1. Introduction

The objective of this research is to develop new models for predicting the risk of post-traumatic osteoarthritis (PTOA) following intra-articular fracture (IAF). We previously developed capabilities to predict PTOA risk from acute fracture severity (measured from pre-op CT) and chronic elevated contact stress (post-op CT) associated with IAFs, but more patient data are needed to make the risk models clinically useful. Prospective studies of PTOA development following IAFs face many challenges. Severe IAFs are not frequently seen in civilian practice, making it difficult to accrue sufficient numbers for clinical study. An added challenge is that to determine if a patient develops PTOA, they may need to be followed for years into the future, threatening subject retention. One of the attractive features of the CT-based measures of mechanical factors pioneered by the Initiating PI is that retrospective studies can include patients who were injured years in the past. Recent military conflicts, which unfortunately produced a substantial number of IAFs (as reported by the Partnering PI), provide a unique opportunity to overcome these challenges and to honor the military personnel who suffered combat-related IAFs. Given their prevalence and severity, and the degree to which these injuries impact long-term function of injured service members, better methods to predict PTOA risk would benefit our current generation of new veterans, as well as future service members at risk for IAF.

2. Keywords

post-traumatic osteoarthritis, CT analysis, intra-articular fractures, clinical outcome

3. Accomplishments

What are the major goals of the project?

Below is the original SOW:

Specific Aim 1: Evaluate pre- and post-treatment CT data from patients with combat-related IAFs to measure fracture severity and post-reduction contact stress exposure	
Major Task 1: Regulatory Approval	Months
Subtask 1.1: Obtain local IRB	1-3
Subtask 1.2: Obtain HRPO approval	4-6
Milestone #1: Regulatory approval received	5-6
Major Task 2: Adapt CT Analysis Methods	Months
Subtask 2.1: Obtain representative CT studies	3
Subtask 2.2: Trial analysis methods with CT studies	1-3
Subtask 2.3: Modify analysis methods as needed	3-9
Milestone #2: Co-author manuscript on methods to analyze combat-related IAFs	9-12
Major Task 3: Subject Identification	Months
Subtask 3.1: Obtain potential subject list with demographic and injury data from DoDTR	7
Subtask 3.2: Screen available CT scans for requisite images for inclusion	8-12
Milestone #3: Subject list finalized	12
Major Task 4: CT Calculations	Months
Subtask 4.1: De-identified CDs compiled and express mailed from Site 2 to Site 1	9-13
Subtask 4.2: CT calculations for injury severity and post-reduction contact stresses	10-18
Milestone #4: Co-author manuscript on fracture severity and post-reduction contact stress measures in patients with combat-related IAFs	18-24

Specific Aim 2: Measure the occurrence of PTOA up to ten years following fracture reduction surgery	
Major Task 5: PTOA radiographic frequency	Months
Subtask 5.1: Identify radiographs for KL grading; multiple investigators do KL grading	9-14
Milestone #5: Co-author paper detailing PTOA incidence and grading for patients with combat-related IAFs	16-20

Specific Aim 3: Quantify the extent to which fracture severity and post-reduction contact stress predict PTOA	
Major Task 6: PTOA symptoms and quality of life	Months
Subtask 6.1: Identify subjects' contact information through DoD and/or VA sources	12-16
Subtask 6.2: Conduct prospective contacting of subjects for outcomes questionnaires	12-28
Milestone #6: Co-author manuscript detailing symptoms and treatment timelines for patients with combat-related IAFs	25-32
Subtask 6.3: Correlate CT-based analysis results with KL grade/PTOA status, questionnaire outcomes, and various radiographic results	28-32
Milestone #7: Co-author manuscript detailing relationships between CT-based results and PTOA outcomes – PTOA risk model	32-36

What was accomplished under these goals?

Major Task 1 (regulatory approval) is now completed.
- Final regulatory approval received (HRPO Log Number A-18855) --- 23-Oct-2015

Major Task 2 (adapt CT analysis methods) is completed, and a manuscript detailing the new methods is now in preparation to be submitted by the end of the calendar year. The new methods were detailed in our revised 2016 Annual Report that was submitted on 01-Mar-2017.

- Modifications required in analysis code outlined and begun --- 15-Mar-2015
- Master's thesis (Kevin Dibbern) detailing new methods completed --- 15-Dec-2015
- Final modifications to analysis code completed --- 01-Jun-2016
- Results presented and published. Abstracts presented: ORS Annual Meeting (19-Mar-2017), OARSI World Congress (27-Apr-2017). Journal articles published in J Orthop Trauma (18-May-2016) and in J Orthop Research (30-Jun-2016).

Major Task 3 (subject identification) is underway, and our collaborator/partner at SAMMC (Dr. Jessica Rivera) continues screening the trauma registry (DoDTR) to identify and enroll subjects meeting inclusion criteria. During the past year, WRAMC queries have been added to the original SAMMC-centric screening, and this produced an uptick in our enrollment. Sixty-eight subjects have been identified/enrolled to date. Additional subjects continue to be screened

Major Task 4 (CT calculations) is underway, and CDs containing de-identified CT data continue to be sent from Site 2 (SAMMC) to Site 1 (Iowa). As cases arrive in Iowa, we are performing calculations of fracture severity and/or post-reduction contact stress. So far, the imaging data for 57 subjects with collectively 95 fractures (see Table 1 for details) have been forwarded to Iowa for analysis, with another 11 subjects identified and their imaging studies requested. We have completed fracture severity analysis of 71 fractures so far.

- CT studies (de-identified) transferred to Iowa for inspection --- 01-Nov-2015
- Additional CT studies transferred to Iowa for inspection and analysis --- 30-Mar-2016
- Fracture severity assessment completed on first subject in the study --- 08-Jun-2016

Detailed report of progress on Major Task 4

In our 2016 Annual Report (submitted 01-Mar-2017, because original submission was deemed insufficient), we presented an early snapshot of ongoing fracture severity assessment in military and civilian subjects. At the time, we had only analyzed fracture energies for 15 tibial pilon and 5 tibial plateau fractures in military subjects. Amongst civilian subjects, we had analyzed 52 tibial pilon and 75 tibial plateau fractures.

We have continued to analyze civilian intra-articular fracture cases, with fracture energies having now been computed for 226 fractures (82 tibial pilon, 88 tibial plateau, and 56 calcaneal). From the military, CT studies for 57 subjects having sustained 95 fractures in 66 limbs have been forwarded to Iowa, and we have completed analysis of 71 (Table 1). By far, the majority of these cases are blast-related. Of note, 12 calcaneal, 2 proximal tibial, and 7 talar fractures had ipsilateral distal tibia fractures (Figure 1). The issue of handling multiple fractures in the same limb is relatively new to us, and we are working to develop strategies for dealing with them.

Table 1. Snapshot of progress

Fracture location	N	Post-op
Calcaneus	32	7
Talus	12	0
Distal tibia	33	8
Proximal tibia	10	4
Distal femur	7	3
Acetabulum	1	0

We were interested to see how the fracture energies vary between military and civilian cases (Table 2 & Figure 2), as well as between isolated and multiple fracture scenarios in a single limb. Clearly, those cases involving multiple fractures in a single limb involve higher fracture energies, although other factors such as variation in loading rates (see next section) may also be involved.

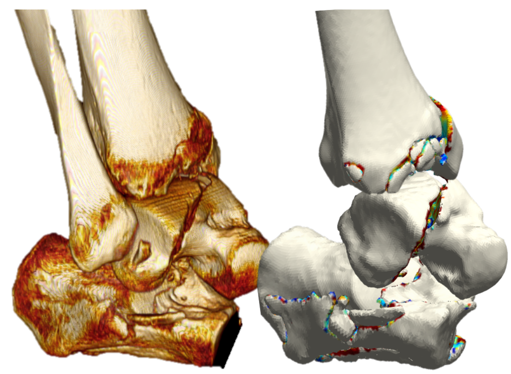
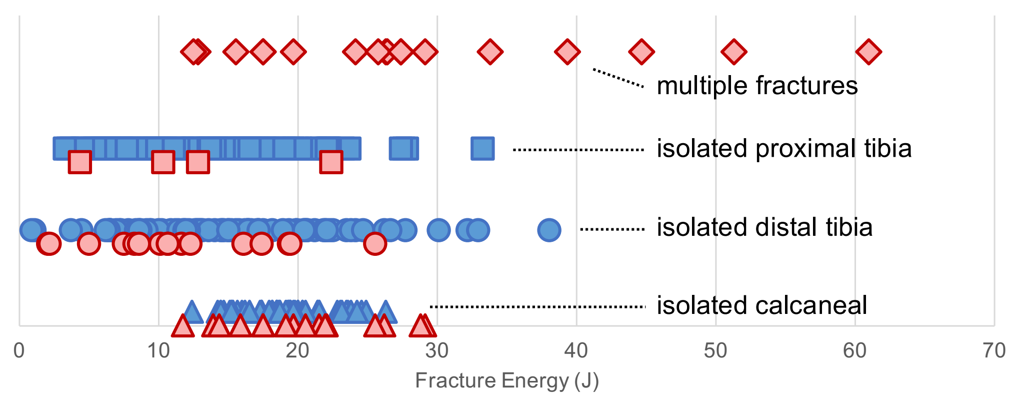


Figure 1. A CT volumetric rendering of a multi-level fracture involving the distal tibia, the talus, and the calcaneus is shown to the left, with the results of fracture energy analysis shown on the right. The colors shown on the interfragmentary surfaces correspond to the local bone densities. The combined fracture energy in this case was 29.1 J.

Table 2. Mixture of multiple vs. isolated fractures

Fracture type/location		N	Fracture Energy (J) Mean	St Dev
multiple	military	18	28.4	13.3
proximal tibia	civilian	88	13.1	6.5
	military	4	12.4	7.5
distal tibia	civilian	82	15.3	7.4
	military	16	11.6	6.5
calcaneus	civilian	56	19.0	3.1
	military	16	20.3	5.2

Figure 2. Graphical comparison of the fracture energies computed in military subjects (red symbols) and civilian subjects (blue symbols), grouped by the location of isolated intra-articular fracture vs. the military multiple fractures.



New, unplanned developments

Recently, we were introduced to a group at the University of Virginia's Center for Applied Biomechanics (http://www.centerforappliedbiomechanics.org) that has been doing cadaveric lower extremity fracture studies for the past 15 years. Dr. Robert Salzar leads the group doing this work and has been our primary point of contact. Their original studies focused on loading rates/conditions associated with common civilian fracture mechanisms, such as in automobile crashes. More recently, they have turned their attention to scenarios more akin to those experienced with blast injuries in the military. The motivation behind their work has been to define physical tolerance limits for the automotive industry and others in the context of protecting against extremity fracture. Data collected during their fracture experiments include accelerations, forces, displacements, bone strains, and video-radiography, with acoustic sensors used to precisely detect fracture initiation.

We immediately recognized this as an opportunity to complement our CT-based post hoc fracture severity analysis work with their direct studies of the actual fracture event. The fact that our post hoc analyses involve a degree of detective work in deducing what happened during fracture introduces the potential for drawing erroneous conclusions, and the direct fracture studies provide a chance to evaluate the detective work while potentially also providing new and valuable insight into the fracture mechanisms.

In their most recent work, Dr. Salzar and his team fractured a series of 10 left-right paired cadaveric lower extremities (below knee) using two different rates of impact loading relevant to the military. The intermediate blast impact accelerates a footplate impactor more slowly than does a high blast impact input (Figure 3). Accelerometric data measured at the footplate impactor

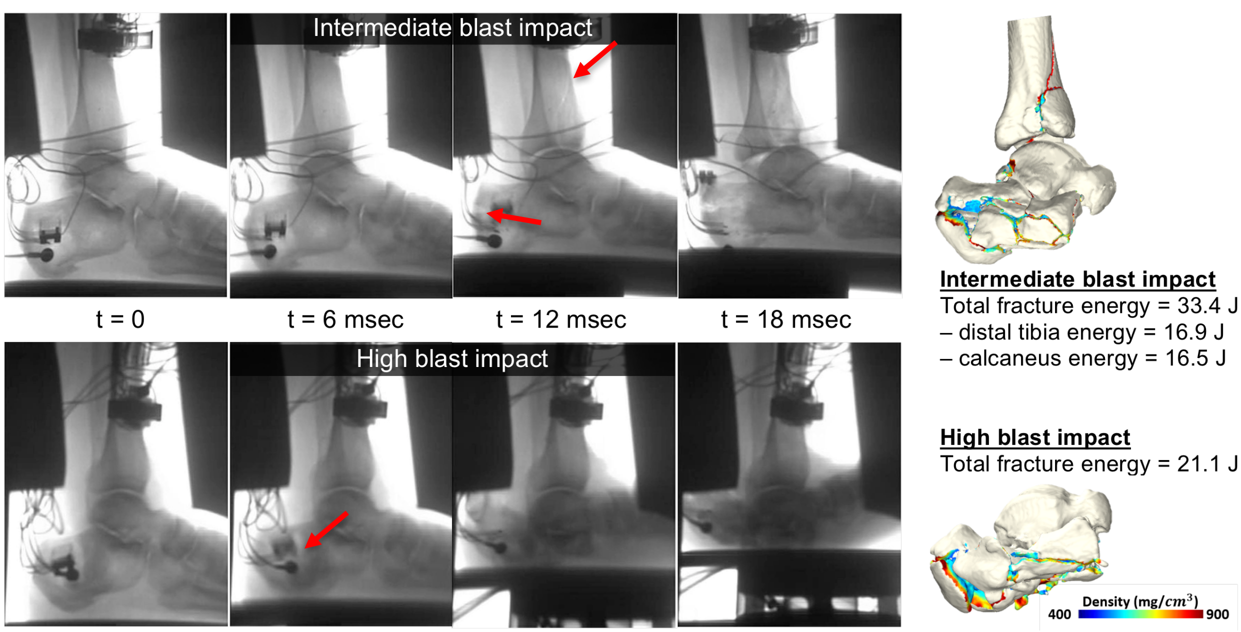


Figure 3. These series of radiographs obtained during impact loading show for the high blast impact (lower row of images) an early fracturing of the calcaneus (t = 6 msec, red arrow), while for the intermediate blast impact (top row) a later fracturing of both the distal tibia and the calcaneus (t = 12 msec, red arrows). Interestingly, the high blast impact involved less fracture energy liberation than did the intermediate blast.

makes it possible to calculate impactor velocities and displacements. A load cell in the footplate allows force to be measured as it develops, synchronized with the accelerometer data. Taken together, these data sources allow for energy input into the system to be measured over time

(Figure 4). Then, using CTs obtained after the fracture, we are able to carry out our post hoc fracture energy analyses in a manner directly comparable to that we use in analyzing actual subject CT studies (Figure 3).

We are working to determine how best to compare post hoc fracture energy assessments with energy transfer measured during the cadaver extremity fractures. We are also analyzing more of the cadaver limbs that were fractured. Meanwhile, we are already gaining new insights regarding blast-related fracture and how it may influence later PTOA development and/or the value of limb salvage vs. amputation. Among new insights that we are currently studying, we have come to believe that the rate with which the blast impacts the plantar aspect of the foot can substantially influence the nature of the resulting injury/fracture. In the specific case shown in Figure 3, the higher rate impact resulted in a more severe injury to the calcaneus, while there was no fracture of the distal tibia. These differences in impact rate-mediated fracture scenarios suggests that it may be possible to alter the design of military vehicles or other protective equipment to try and protect a soldier from the worst of these horrible fracture events.

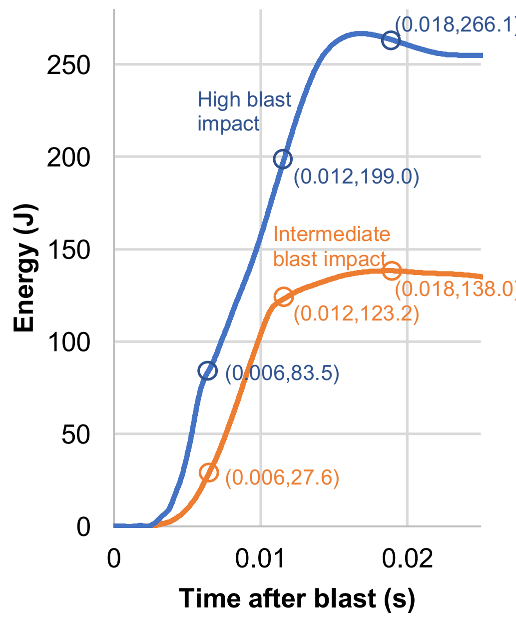


Figure 4. Energy development following impact blast. The circles on the two data curves coincide with the times for the radiographic images in Figure 3. By virtue of the higher rate of loading in the high blast impact, energy develops more quickly. This appears to influence the nature of the corresponding fractures, which occurred at 6 msec for the high blast and at 12 msec for intermediate.

Major Tasks 5 (PTOA radiographic frequency) and 6 (PTOA symptoms and quality of life) are beginning to be addressed, but all indications are that we should be able to proceed with our remaining major tasks as originally planned.

In a preliminary analysis of our data, we sought to see if fracture energy can predict painful and activity-limiting PTOA, which contributes to late amputation in military blast injuries. Twenty of our military subjects presenting with tibial pilon fractures resulting from blast injuries were studied, with 15 patients having suitable follow-up data currently available. These were the first analyzed from the larger series of patients that we are following. Fracture energy and articular comminution were computed from pre-operative CT scan data using our newly developed methods. The CT scans were segmented to identify and generate 3D surface models of all bone fragments. Bone surfaces were then classified into intact and *de novo* fracture surfaces using a trained classification algorithm. Location-specific bone densities were then used to scale interfragmentary fracture surface areas by density-dependent energy release rates to obtain the fracture energy. Articular comminution was incorporated by quantifying the articular fracture edge length, defined as the length of the edge at the intersection between interfragmentary and subchondral bone surfaces. Outcomes were evaluated using KL grading of OA from radiographs and by the rate of successful limb salvage.

Fracture energies ranged from 1.3 to 28.7 J with a mean$\pm$SD of 11.9$\pm$8.0 J. Articular fracture edge length ranged from 18.5 to 256.1 mm with a mean$\pm$SD of 115.0$\pm$45.3 mm. Of the 15 patients with follow-up data available, 1 limb resulted in amputation secondary to soft tissue reconstructive challenges and 4 limbs were amputated due to the patients' pain and resultant activity restriction. Of the limbs that were amputated late, two had a KL grade of 3 and two had a

KL grade of 4 (both representing advanced ankle OA). There was a statistically significant difference in the fracture energies of the amputation and retained limb groups (17.4 J vs 6.6 J, respectively; p=0.0059) while articular fracture edge length differences trended towards significance (135.1 vs 105.3 mm; p=0.056). When the two predictors were combined, an objective fracture severity score nearly perfectly predicted amputation (Figure 5). There were no significant differences in fracture energy or articular fracture edge length for different KL grades in this preliminary investigation.

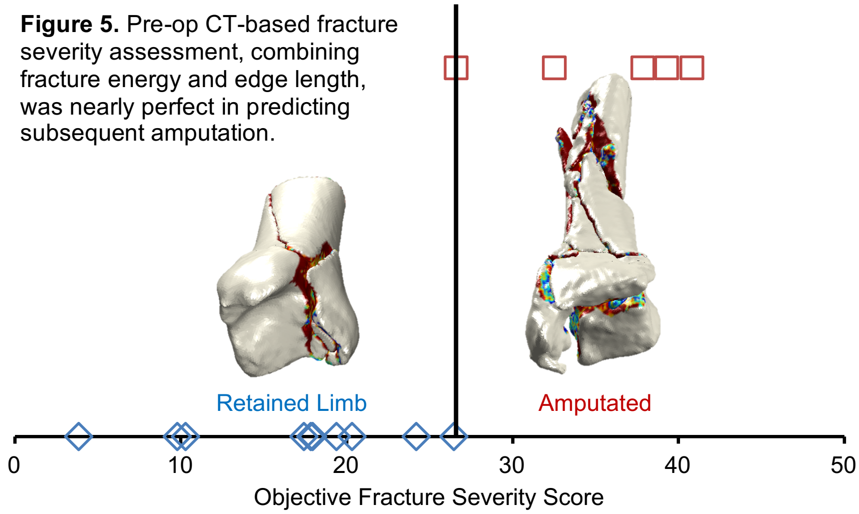


Figure 5. Pre-op CT-based fracture severity assessment, combining fracture energy and edge length, was nearly perfect in predicting subsequent amputation.

This preliminary investigation into pre-op prediction of injury severity may offer insights into long term prognosis of such injuries, but we await additional fracture analysis of more cases to support these findings. Higher-energy injuries of the tibial pilon present complex treatment decisions. Objective measures of fractures severity may eventually provide pre-operative predictions of patient outcomes that can help guide initial operative management in cases where challenging decisions may exist.

What opportunities for training and professional development has the project provided?

Mr. Kevin Dibbern, the graduate research assistant on this project, is concurrently pursuing a PhD in Biomedical Engineering. Dr. Anderson serves as his primary advisor, and in that capacity not only directs Mr. Dibbern's work, but also mentors him in related technical and professional development matters. This involves bi-weekly one-on-one meetings, having Mr. Dibbern give regular presentations in the laboratory related to this work, and having Mr. Dibbern attend national/international conferences at which his work is presented.

How were the results disseminated to communities of interest?

During the past year, our most recent findings were presented at multiple venues, with a specific focus on military centric meetings. We presented at the Military Health System Research Symposium, the Limb Lengthening and Reconstruction Society, and at annual meetings of the Orthopaedic Research Society and of the Orthopaedic Trauma Association. We have also submitted an abstract for presentation at the 13th Annual Extremity War Injuries Symposium, sponsored by AAOS, SOMOS, OTA, and the ORS.

What do you plan to do during the next reporting period to accomplish the goals?

In the coming quarter, work will continue identifying and enrolling subjects in the study at the SAMMC site. Analysis will be ongoing as relevant imaging data continue to be received in Iowa. It may be valuable for Dr. Anderson and/or Mr. Dibbern to travel to the University of Virginia site during the next quarter to foster that collaboration. During this coming quarter, we will be continuing work on **Major Task 5**, which involves identifying, finding, and grading follow-up radiographs for PTOA status (KL grading).

4. **Impact**

What was the impact on the development of the principal discipline(s) of the project?

Nothing to Report

What was the impact on other disciplines?

Nothing to Report

What was the impact on technology transfer?

Nothing to Report

What was the impact on society beyond science and technology?

Nothing to Report

5. **Changes/Problems**

Changes in approach and reasons for change

Nothing to Report

Actual or anticipated problems or delays and actions or plans to resolve them

During the past year, Dr. Rivera (our Partnering PI) and her team at SAMMC came to believe that they were not going to be able to meet their enrollment targets relying solely on queries at SAMMC. This led them to reach out to colleagues at WRAMC, which has led to a new source of enrollment that has boosted our numbers.

Changes that had a significant impact on expenditures

Nothing to Report

Significant changes in use or care of human subjects, vertebrate animals, biohazards, and/or select agents

Nothing to Report

Significant changes in use or care of human subjects

Nothing to Report

Significant changes in use or care of vertebrate animals.

Not Applicable

Significant changes in use of biohazards and/or select agents

Not Applicable

6. **Products**

Publications, conference papers, and presentations

- Journal publications

1. Kempton LB, Dibbern KA, Anderson DD, Morshed S, Higgins TF, Marsh JL, McKinley TO. Objective metric of energy absorbed in tibial plateau fractures corresponds well to

clinician assessment of fracture severity. J Orthop Trauma 2016, May 26;30(10):551-6. PMC5035182. Federal support acknowledged.

2. Dibbern K, Kempton LB, Higgins TF, Morshed S, McKinley TO, Marsh JL, Anderson DD. Fractures of the tibial plateau involve similar energies as the tibial pilon but greater articular surface involvement. J Orthop Res. 2017;35(3):618–624. PMC5218984. Federal support acknowledged.

- Books or other non-periodical, one-time publications.

1. Dibbern K. Objective CT-Based Method for Quantifying Articular Fracture Severity: Clinical Application in Multiple Joints. 2015. M.S. Thesis, Department of Biomedical Engineering, The University of Iowa.

- Other publications, conference papers, and presentations.

1. Kempton LB, Dibbern K, Anderson DD, Morshed S, Higgins T, Marsh JL, McKinley T. Objective metric of energy absorbed in tibial plateau fractures corresponds well to clinician assessment of fracture severity. 31st Annual Meeting of the Orthopaedic Trauma Association, October 7-10, 2015, San Diego, CA. (*)

2. Dibbern KN, Kempton LB, Higgins TF, McKinley TA, Marsh JL, Anderson DD. Energy absorbed in fracturing is similar in tibial plateau and pilon fractures over a full spectrum of severity. 83rd Annual Meeting of the American Academy of Orthopaedic Surgeons, March 1-5, 2016, Orlando, FL. (*)

3. Kempton LB, Dibbern K, Anderson DD, Morshed S, Higgins T, Marsh JL, McKinley T. CT-based metric of tibial plateau fracture energy corresponds well to clinician assessment of fracture severity. 83rd Annual Meeting of the American Academy of Orthopaedic Surgeons, March 1-5, 2016, Orlando, FL. (*)

4. Dibbern KN, Kempton LB, McKinley TA, Higgins TF, Marsh JL, Anderson DD. Quantifying tibial plateau fracture severity: Fracture energy agrees with clinical rank ordering. 62nd Annual Meeting of the Orthopaedic Research Society, March 5-8, 2016, Orlando, FL. (*)

5. Dibbern KN, Higgins TF, Kempton LB, McKinley TA, Marsh JL, Anderson DD. Objective fracture energy assessment of tibial plateau fractures loosely corresponds to Schatzker classification. 62nd Annual Meeting of the Orthopaedic Research Society, March 5-8, 2016, Orlando, FL. (*)

6. Rao K, Dibbern KN, Phisitkul P, Marsh JL, Anderson DD. Relating fracture severity to post-traumatic osteoarthritis risk after intra-articular calcaneal fractures. 62nd Annual Meeting of the Orthopaedic Research Society, March 5-8, 2016, Orlando, FL.

7. Mosqueda JM, Dibbern KN, Willey MC, Marsh JL, Anderson DD. Elevated contact stress after surgical reduction of acetabular fractures correlates with progression to post-traumatic osteoarthritis. 40th Annual Meeting of the American Society of Biomechanics, August 2-5, 2016, Raleigh, NC.

8. Dibbern KN, Kempton LB, Higgins TF, McKinley TO, Marsh JL, Anderson DD. Clinical fractures of the tibial plateau involve similar energies as the tibial pilon. 40th Annual Meeting of the American Society of Biomechanics, August 2-5, 2016, Raleigh, NC. (*)
9. Rao K, Dibbern KN, Phisitkul P, Marsh JL, Anderson DD. Post-traumatic OA risk relative to intra-articular calcaneal fracture severity. 32nd Annual Meeting of the Orthopaedic Trauma Association, October 5-8, 2016, National Harbor, MD.
10. Dibbern KN, Kern AM, Anderson DD. A universally applicable, objective CT-based method for quantifying articular fracture severity. 63rd Annual Meeting of the Orthopaedic Research Society, March 19-22, 2017, San Diego, CA.
11. Holland TC, Dibbern KN, Marsh JL, Anderson DD, Willey MC. Objective prediction of post-traumatic OA risk following acetabular fractures based on severity. 63rd Annual Meeting of the Orthopaedic Research Society, March 19-22, 2017, San Diego, CA.
12. Dibbern KN, Willey MC, Phisitkul P, Glass NA, Marsh JL, Anderson DD. Fracture severity predicts OA risk following intra-articular fractures. 2017 OARSI World Congress on Osteoarthritis, April 27–30, 2017, Las Vegas, Nevada.
13. Anderson DD. Pathomechanics of post-traumatic OA development in the military following articular fracture. Clinical and Rehabilitative Medicine Research Program Osteoarthritis Therapy In Progress Review Meeting, May 8–9, 2017, Fort Detrick, Maryland.
14. Rivera JC, Dibbern KN, Marsh JL, Anderson DD. Objective CT-based assessment of severity in articular fractures of the tibial pilon. 26th Annual Scientific Meeting of the Limb Lengthening and Reconstruction Society, July 21–22, 2017. Park City, Utah.
15. Dibbern KN, Rivera J, Marsh JL, Anderson DD. Objective CT-based assessment of severity in articular fractures of the tibial pilon. 2017 Military Health System Research Symposium, August 27–30, 2017, Kissimmee Florida.
16. Dibbern KN, Rivera JC, Marsh JL, Anderson DD. Objective assessment of tibial pilon articular fracture severity predictive of secondary amputation. 64th Annual Meeting of the Orthopaedic Research Society, March 10-13, 2018, New Orleans, LA.
17. Dibbern KN, Rivera JC, Marsh JL, Anderson DD. Objective metrics of tibial pilon fracture severity predict secondary amputation. 13th Annual Extremity War Injuries Symposium (submitted), January 21-23, 2018, Washington, DC.

Website(s) or other Internet site(s)

Nothing to Report

Technologies or techniques

Our prior objective, CT-based methods for determining the energy expended in a bone fracture were extended to enable their use in more fracture types. The new methodology requires only a pre-operative CT-scan of the fractured joint. The CT images are then segmented, identifying all bone fragments to generate 3D models of the fracture fragments. Surfaces are then smoothed to remove imaging artifacts and to prepare the data for use in a surface classification algorithm. An automated classifier then identifies fractured surfaces on the fragments, with a

graph cut method used to create a clear boundary between the intact and fractured bone surfaces. Manual adjustment of this boundary is performed to finalize the fractured surface identification. The CT Hounsfield Unit intensities are then sampled along the fractured surface for use in obtaining a bone density distribution over the surface. The fractured areas are then scaled by these location specific densities and multiplied by a density dependent energy release rate to obtain the fracture energy. Articular comminution can be quantified by measuring the fracture edge length along the articular surface from the fractured surface boundaries. The new methodology was validated by comparing the fracture energies obtained for a series of 20 pilon fractures that had previously been assessed using the existing methods.

We recognize the need for broad dissemination of the research methods developed in the course of this work that allow study of the pathways responsible for PTOA. Perhaps the most effective means for sharing the techniques is through the presentation of our findings at scientific meetings and as peer-reviewed published manuscripts. In the latter case, we will submit or have submitted on our behalf to the National Library of Medicine's PubMed Central an electronic version of any final, peer-reviewed manuscripts upon acceptance for publication, to be made publicly available no later than 12 months after the official date of publication. We will strive to produce such scientific outputs in a timely manner and to report on all relevant data derived during the project in as broad a range of venues as possible.

Inventions, patent applications, and/or licenses

Nothing to Report

Other Products

Nothing to Report

7. **Participants & Other Collaborating Organizations**

What individuals have worked on the project?

Name: Donald D. Anderson, PhD
Project Role: PI
Researcher Identifier (e.g. ORCID ID): 0000-0002-1640-6107
Nearest person month worked: 2.4
Contribution to Project: Dr. Anderson leads the research team at the University of Iowa, guiding development and analysis related to the project.

Name: J. Lawrence Marsh, MD
Project Role: Investigator
Nearest person month worked: 0.6
Contribution to Project: Dr. Marsh is the clinical lead at the University of Iowa, providing insight regarding the scope of the clinical problem and ensuring clinical applicability of decisions related to the project.

Name: M. James Rudert, PhD
Project Role: Investigator
Nearest person month worked: 4

Contribution to Project: Dr. Rudert, an expert in mechanical measurement and fracture testing/simulation work, works closely with Mr. Dibbern to support measurements and computation.

Name: Kevin Dibbern, MS
Project Role: Graduate Research Assistant
Nearest person month worked: 6
Contribution to Project: Mr. Dibbern is actively involved developing algorithms, writing analysis code, and performing analysis of the CT data.

Has there been a change in the active other support of the PD/PI(s) or senior/key personnel since the last reporting period?

Nothing to Report

What other organizations were involved as partners?

Nothing to Report

8. **Special Reporting Requirements**

COLLABORATIVE AWARDS: The Collaborating/Partnering PI at SAMMC (Dr. Jessica Rivera) is submitting a separate progress report for that site.

9. **Appendices**

A comprehensive collection of journal publications, a Master's thesis, and abstracts (please see above *Products* for a complete listing) that supplements, clarifies and supports the text of this report are attached as appendices.

Objective Metric of Energy Absorbed in Tibial Plateau Fractures Corresponds Well to Clinician Assessment of Fracture Severity

Laurence B. Kempton, MD, Kevin Dibbern, BS,† Donald D. Anderson, PhD,† Saam Morshed, MD,‡ Thomas F. Higgins, MD,§ J. Lawrence Marsh, MD,† and Todd O. McKinley, MD**

Objectives: Determine the agreement between subjective assessments of fracture severity and an objective computed tomography (CT)-based metric of fracture energy in tibial plateau fractures.

Methods: Six fellowship-trained orthopaedic trauma surgeons independently rank-ordered 20 tibial plateau fractures in terms of severity based on anteroposterior and lateral knee radiographs. A CT-based image analysis methodology was used to quantify the fracture energy, and agreement between the surgeons' severity rankings and the fracture energy metric was tested by computing their concordance, a statistical measure that estimates the probability that any 2 cases would be ranked with the same ordering by 2 different raters or methods.

Results: Concordance between the 6 orthopaedic surgeons ranged from 82% to 93%, and concordance between surgeon severity rankings and the computed fracture energy ranged from 73% to 78%.

Conclusions: There is a high level of agreement between experienced surgeons in their assessments of tibial plateau fracture severity, and a slightly lower agreement between the surgeon assessments and an objective CT-based metric of fracture energy. Taken together, these results suggest that experienced surgeons share a similar understanding of what makes a tibial plateau fracture more or less severe, and an objective CT-based metric of fracture energy captures much but not all of that information. Further research is ongoing to characterize the relationship between surgeon assessments of severity, fracture energy, and the eventual clinical outcomes for patients with fractures of the tibial plateau.

Key Words: tibial plateau fracture, fracture energy, quantifying fracture severity

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INTRODUCTION

Fracture severity is commonly assessed by treating orthopaedic surgeons to determine prognosis and decide optimal treatment. Outcomes of intraarticular fractures are influenced by multiple patient, surgeon, and injury factors. The location of a fracture and its morphology, the quantity of articular surface involvement, and the extent of acute mechanical damage all play a role in defining the severity of a fracture. Fracture "severity" spans a spectrum from low to high. Low-severity fractures have characteristics such as minimal displacement or comminution and are thought to have an excellent prognosis with nonoperative treatment. High-severity fractures have characteristics like extensive displacement and comminution and are generally indicated for operative treatment with good to fair prognosis.

These indices, taken together, clearly indicate individual injury specificity. Orthopaedic surgeons formulate treatment strategies based largely on subjective criteria and clinical experience while accounting for patient-specific demographic and medical conditions. However, subjective methods of fracture assessment such as morphology and classification are often poorly reproducible among orthopaedic surgeons and are inherently unreliable.[1–3] There is a risk that relying on such methods may lead to poorly conceived treatment algorithms because they are not grounded in objective data.

The greater the amount of energy dissipated in the creation of a fracture (ie, the fracture energy), the greater the fracture severity. Accurate and reliable measures of the fracture energy can provide objective data for orthopaedic surgeons to use in making treatment decisions and predicting prognosis.

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Previous investigations have demonstrated that objective computed tomography (CT)-based measures of fracture energy in tibial pilon fractures correlate with (1) surgeon assessment of injury severity and (2) 2-year radiographic and functional outcomes.[4,5] In this work, we explored whether this technique of objective fracture energy measurement could also be used to stratify the severity of tibial plateau fractures in a manner that would agree with expert opinions of fracture severity. Specifically, we hypothesized that an objective CT-based measure of fracture energy would correspond to subjective surgeon assessment of fracture severity.

MATERIALS AND METHODS

A fellowship-trained orthopaedic trauma surgeon (TOM) purposefully selected 20 cases from a series of 50 consecutive tibial plateau fractures to represent a full spectrum of fracture severity and to avoid having multiple fractures cluster around a common level of severity. Fracture classifications included orthopaedic trauma association (OTA) 41-B3 and 41-C3, reflecting the use of CT in assigning classifications and a heavy emphasis on articular surface involvement and depression.[6] Patients sustaining the fractures ranged in age from 18 to 70 years old. There were 12 males and 8 females. Our Institutional Review Board approved use of the patient data. See **Table**, **Supplemental Digital Content 1** (http://links.lww.com/BOT/A715) for a summary of demographic information.

Six fellowship-trained orthopaedic trauma surgeons from 4 separate institutions independently rank-ordered the fractures in order of severity based on the appearance of the fractures on AP and lateral knee radiographs. The only instructions given to the raters were to rank the cases in order of least to most severely injured. Subjectively, they used the number and size of fragments, the amount and direction of displacement, percentage of articular surface involved, and whatever other features they felt were important based on their clinical experience. Raters were blinded to independently obtain CT-derived data and patient information.

A previously validated CT-based image analysis approach was used to quantify the fracture energy based on measurement of the fracture-liberated surface area and accounting for bone density. This method has been shown to be accurate in calculating fracture energy (ie, the amount of energy dissipated in fracturing the bone),[7,8] but the extent of its clinical utility is still under investigation. Fracture energy is expressed in the units of Joules (J), which are equivalent to Newton-meters or kg-m^2/s^2. Software, custom-written in MATLAB, was used to identify all fracture fragments working from standard-of-care axial CT image data. The surfaces of the fragments were then classified as subchondral, cortical, or interfragmentary based on their associated CT intensities and their local geometric character (surface roughness, curvatures, etc). The surface classifications were subsequently manually confirmed to be accurate, or modified as needed, by an experienced analyst (Fig. 1). The interfragmentary surface areas of all the fracture fragments were summed to provide a single aggregate measure of the fracture-liberated surface area. Bone density values were obtained based on previously established relationships with Hounsfield intensity of CT pixels,[9] and the fracture-liberated surface areas were scaled accordingly to reflect the influence of bone density on the fracture properties. Fracture energy was calculated from a previously validated formula based on the fracture mechanics principle that energy is directly proportional to fracture-liberated surface area scaled by bone density in a brittle solid.[7,8]

We tested our hypothesis by comparing the surgeon rank orderings of fracture severity in this series of tibial plateau fractures with CT-based measurements of fracture energy. The agreement between fracture severity assessments among the surgeons, and between each of the surgeons and the fracture

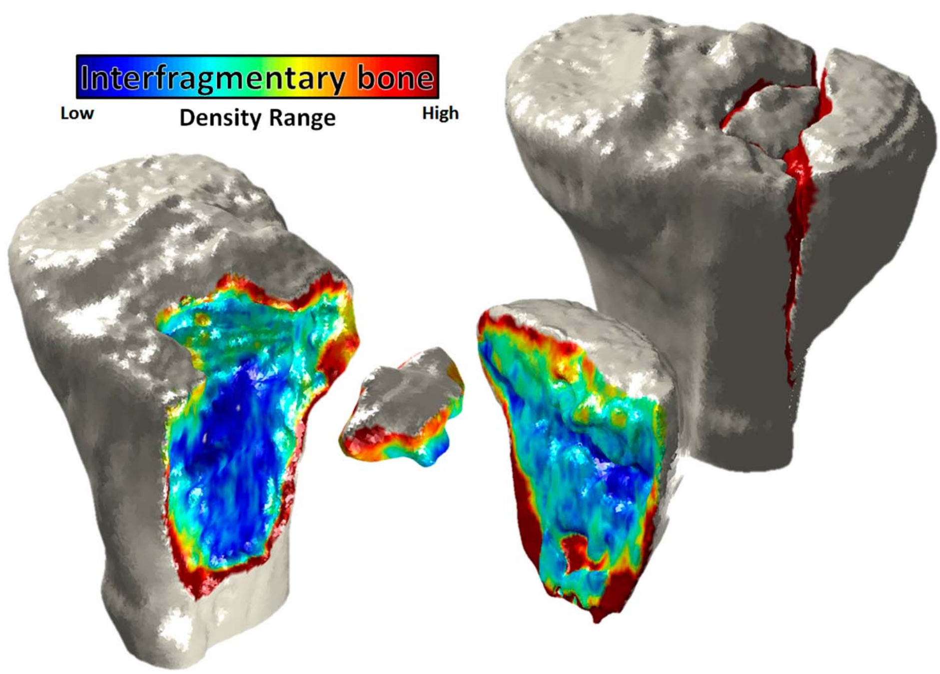

FIGURE 1. Custom-written software was used to measure the surface area of the fracture-liberated cancellous (interfragmentary) bone surfaces, colored according to their local density in the exploded view to the left. The fracture-liberated surface area and bone densities were both used to calculate fracture energy. **Editor's Note:** A color image accompanies the online version of this article.

energy metric, was tested by computing their concordance. The injury severity rankings of 2 cases were deemed concordant if the case with the higher ranking of injury severity by 1 rater/metric also had the higher ranking by a second. The concordance was calculated as the number of concordant pairs divided by the total number of possible pairings. This sample-based statistical measure was used to estimate the probability that 2 cases would be ranked with the same ordering. Random assignment of fracture severity by 2 reviewers would be expected to result in a concordance of 0.5 because any case pairing would have a 50% chance of being concordant.

RESULTS

Fracture energies ranged from 5.5 J to 36.7 J (see **Table**, **Supplemental Digital Content 1**, http://links.lww.com/BOT/A715). There was a high level of agreement between the 6 experienced surgeons in their assessments of tibial plateau fracture severity, with concordances ranging from 82% to 89%, with a mean of 85% (Fig. 2). The concordance between surgeon severity rankings and the fracture energy severity ranking were slightly less high, ranging from 73% to 78%, with a mean of 74%.

Case 19 (as ranked by rater 1) is an example of excellent agreement between orthopaedic surgeons and fracture energy. Severity rankings ranged from 17 to 20 with a fracture energy of 24.5 J (Fig. 3). Substantial articular surface comminution and normal bone density led to a high fracture energy calculation. This feature, as well as substantial fracture displacement, knee dislocation, and bicondylar fracture morphology all contributed to high ranking by the orthopaedic surgeons. Despite the good overall agreement observed between surgeon assessments of fracture severity and the fracture energy metric, there were some notable exceptions. Case 18 demonstrated substantial discrepancy between the objective fracture energy metric and all 6 subjective ratings (Fig. 4). The orthopaedic surgeons all rated this fracture as high in severity, whereas the fracture energy value was modest (11.9 J). The radiographs demonstrate significant fracture malalignment, which would not be reflected in the fracture energy. In contrast, case 7 was a clear outlier with a much higher fracture energy value (17.9 J) relative to the low severity rank assigned by all 6 raters (Fig. 5). The common "split-depression" (OTA 41-B3) was typically deemed lower severity by all surgeons, but closer inspection of the sagittal CT section demonstrates significant comminution leading to a higher fracture energy measurement.

DISCUSSION

The purpose of this study was to determine whether a CT-based fracture energy metric could provide an objective, quantifiable measure of tibial plateau fracture severity by comparing it to the current gold standard, subjective expert surgeon opinion. We found a high level of agreement (85%) regarding fracture severity among the 6 orthopaedic trauma subspecialists. The level of agreement between surgeon assessments of fracture severity and fracture energy was 74%, suggesting that fracture energy has clinical relevance. These results demonstrate that fracture energy reasonably mirrors expert opinion regarding the relative fracture severity over a full spectrum of tibial plateau fractures. This builds on the findings of previous investigations of tibial pilon fractures and shows that fracture energy may be used as a measure of injury severity in other intraarticular fractures as well.

The two major benefits of using fracture energy rather than clinician assessment are its ability to physically quantify severity and its objective nature. Quantifying fracture energy allows for distribution of fracture severity over continuous scales ranging from the entire spectrum of injury severity to subtle differences not appreciated by clinical assessment. In contrast, current classification schemes place fractures into one of several categories and often do not distinguish between substantially different injuries. Objectivity in calculating fracture energy is also valuable because it prevents clinician bias and disagreement resulting from subjective assessments and ensures reproducibility of calculations through rigorous algorithms.

The Schatzker classification and OTA classification are 2 common subjective methods that categorize tibial plateau fractures and convey information about fracture severity. The

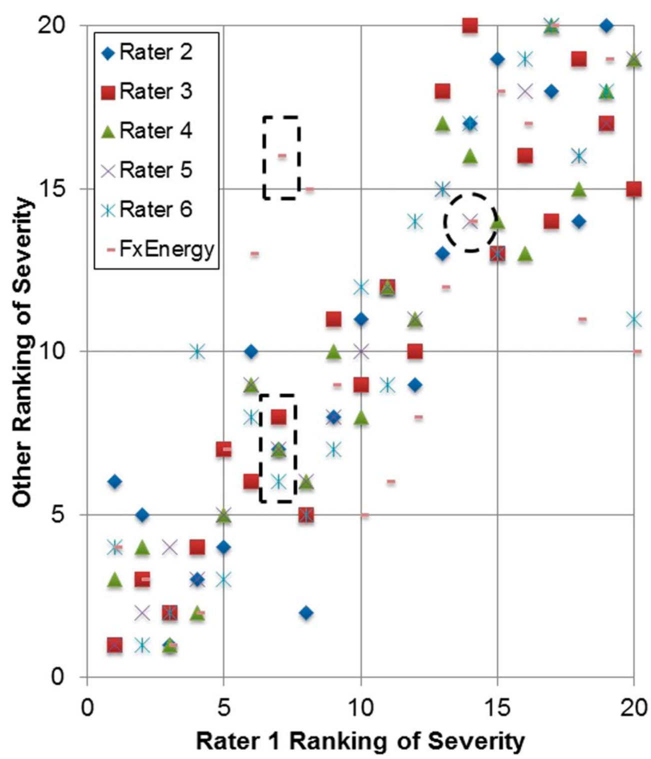

FIGURE 2. Representative rank ordering of fracture severity by 6 orthopaedic trauma surgeons and by fracture energy. The y-axis represents severity ranking as assigned by raters 2–6 and according to the calculated fracture energy. The x-axis represents the rank ordering of rater 1. As an example, there was high agreement between rater 1 and raters 2 through 6 at rater-1 injury number 7, but this fracture's rank according to fracture energy calculation was much higher (black dashed boxes). At rater-1 injury number 14, the rank according to fracture energy was the same as the rank assigned by raters 1 and 5 (dashed circle). **Editor's Note:** A color image accompanies the online version of this article.

FIGURE 3. Example of high level of agreement between orthopaedic surgeons and fracture energy calculation. These AP and lateral knee radiographs demonstrate a bicondylar tibial plateau fracture with substantial articular surface comminution and displacement and an associated knee dislocation.

interobserver reliability of assigning fractures within these 2 classifications based on radiographs ranges from 0.38 to 0.47 and from 0.36 to 0.43 (Kappa statistic), respectively.[1–3,10] When the classifications are based on CT, the reliabilities increase to 0.76 and 0.73, respectively.[10] Although concordance values cannot be directly compared with correlation, our concordance rates of 73%–78% fracture energy and surgeon ranking suggest a similar or better level of agreement relative to current classification strategies. Although this study does not necessarily support incorporating fracture energy calculations into clinical practice, it demonstrates clinical relevance of fracture energy. Therefore, fracture energy can be used to quantify injury severity as an objective, continuous variable in studies comparing 2 groups of fractures to determine extent of group similarity. This is superior to common methods of comparing severity between groups using fracture classification.

It may also be that fracture energy predicts outcomes as a function of treatment. Perhaps excellent outcomes can be expected after nonoperative treatment of a low-severity fracture (fracture energy of 6 J), whereas poor outcomes with nonoperative treatment (and good outcome with operative treatment) can be expected for a high-severity fracture (fracture energy of 30 J). If that were the case, then measurement of fracture energy would be helpful to determine operative indications, as well as predict future patient function.

There are several inherent inaccuracies and discrepancies in CT-based measurements and surgeon observations. First, the fracture energy calculation was based solely on fracture-liberated surface area and bone density. It does not

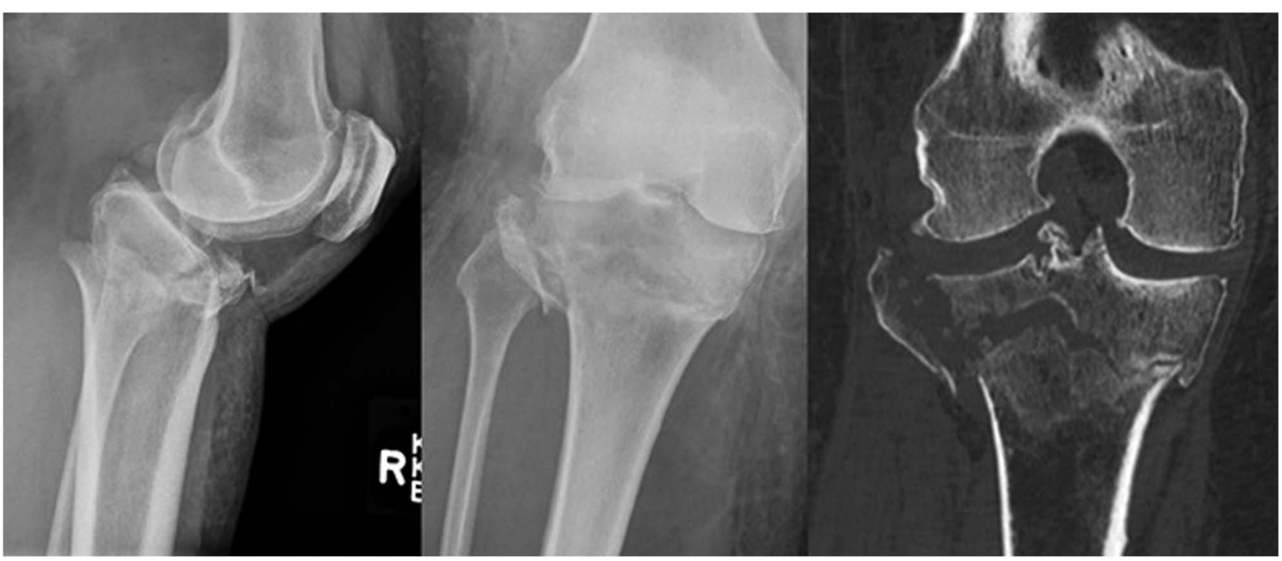

FIGURE 4. Example of high clinician ranking but modest fracture energy. These AP and lateral knee radiographs and a representative coronal CT cut demonstrate osteopenia and substantial metaphyseal impaction without many separate pieces of comminution. The ranking surgeons considered these factors in their assessment of severity, but the fracture energy calculation did not.

FIGURE 5. Example of high fracture energy but low surgeon ranking. These AP and lateral knee radiographs and representative sagittal CT cut demonstrate a fracture that surgeons ranked low in severity because of minimal comminution and depression at the weight-bearing portion of the articular surface and very little overall fracture displacement. However, comminution throughout the posterior central portion of the tibial plateau substantially contributed to an increased fracture energy calculation.

yet account for other fracture features observed by surgeons, such as fracture displacement, malalignment (Fig. 4), fracture morphology (eg, extent of articular surface comminution vs. metaphyseal comminution), or the ease of fixing the fracture, all of which may influence outcomes. Decreased bone density also directly reduces objective energy measurements. In contrast, it is possible that surgeons examining radiographs would ascribe a higher severity to an osteopenic fracture based on fracture fixation difficulties often encountered in such injuries. This would lead to higher severity ranking by surgeons compared with lower fracture energy calculations. Another factor leading to higher surgeon ranking of severity relative to fracture energy is that the surface area metric is based on brittle material assumptions[11] and does not account for plastic deformation. Therefore, impacted metaphyseal and articular surface fragments, which often have significant compaction of underlying trabecular bone, may have absorbed higher levels of energy than were measured. This could lead to an artificially lower fracture energy calculation, particularly in fractures with significant articular surface comminution. Finally, a limitation of the study unrelated to the technique for measuring fracture energy is that the orthopaedic surgeons judged fracture severity based solely on plain radiographs, but the fracture energy calculation was based on CT data. Therefore, there were likely instances in which certain fracture characteristics not appreciated on radiographs may have led to underestimation of fracture severity by surgeon assessment.

Fracture displacement, undeniably one of the most important clinical assessment criteria, was not included in the fracture energy metric. This was because regression analysis in our previous work[7] identified fracture energy and articular comminution as statistically significant post-traumatic osteoarthritis predictors ($P < 0.01$), but not fragment displacement ($P = 0.35$). Actually, fracture energy and fracture displacement were only loosely linked in that work. This may partly be because injury CT scans are often obtained after the application of a temporary external distractor.

This work is a preliminary interrogation of a novel method to yield objective evidence that may eventually prove useful to guide treatment decisions. However, there are no data yet from our study that correlate fracture energy and clinical outcomes. Surgeon rank-order assessment of fracture severity is a reasonable subjective index but has no objective jurisdiction in predicting outcomes. In this study, we chose to use this subjective measure as there is currently no other standard against which to compare fracture energy. Further investigation is ongoing to determine whether quantified relationships between objective fracture energy indices and objective measurements of clinical outcomes can be established.

In conclusion, an objective CT-based measurement of fracture energy demonstrated good concordance with fellowship-trained orthopaedic trauma surgeon subjective assessment of injury severity in tibial plateau fractures, adding to previous work reporting similar findings for tibial pilon fractures. Ongoing investigation will determine the clinical utility of these measurements.

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Fractures of the Tibial Plateau Involve Similar Energies as the Tibial Pilon but Greater Articular Surface Involvement

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ABSTRACT: Patients with tibial pilon fractures have a higher incidence of post-traumatic osteoarthritis than those with fractures of the tibial plateau. This may indicate that pilon fractures present a greater mechanical insult to the joint than do plateau fractures. We tested the hypothesis that fracture energy and articular fracture edge length, two independent indicators of severity, are higher in pilon than plateau fractures. We also evaluated whether clinical fracture classification systems accurately reflect severity. Seventy-five tibial plateau fractures and 52 tibial pilon fractures from a multi-institutional study were selected to span the spectrum of severity. Fracture severity measures were calculated using objective CT-based image analysis methods. The ranges of fracture energies measured for tibial plateau and pilon fractures were 3.2–33.2 Joules (J) and 3.6–32.2 J, respectively, and articular fracture edge lengths were 68.0–493.0 mm and 56.1–288.6 mm, respectively. There were no differences in the fracture energies between the two fracture types, but plateau fractures had greater articular fracture edge lengths ($p < 0.001$). The clinical fracture classifications generally reflected severity, but there was substantial overlap of fracture severity measures between different classes. Similar fracture energies with different degrees of articular surface involvement suggest a possible explanation for dissimilar rates of post-traumatic osteoarthritis for fractures of the tibial plateau compared to the tibial pilon. The substantial overlap of severity measures between different fracture classes may well have confounded prior clinical studies relying on fracture classification as a surrogate for severity.
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Keywords: tibial plateau; tibial pilon; fracture severity; post-traumatic OA

Post-traumatic osteoarthritis (PTOA) commonly occurs following a variety of joint injuries. Articular fractures of the lower extremity are particularly at risk of PTOA, and they often result from similar injury mechanisms. Despite similarities in the injuries, PTOA develops in 23–44% of tibial plateau fractures before 15 years[1,2] but in as many as 74% of tibial pilon fractures.[3] The reasons for this difference are not well understood. It is known that outcomes of articular fractures are influenced by the severity of the damage sustained at the time of injury and as a result of abnormal loading associated with changes to articular congruity, joint alignment, and joint stability after healing.[4–6]

The primary goals in treating articular fractures are to restore limb alignment and precisely reduce any articular displacement to decrease the likelihood of PTOA. The severity of the fracture correlates highly with the risk of PTOA, so treating surgeons have adopted fracture severity assessment methods to aid in their treatment decision-making. However, conventional systems for classifying fractures and their severity are highly subjective, have poor reliability, and cannot reliably predict risk of PTOA.[7–13]

The damage sustained at the time of injury can be objectively assessed though physical manifestations of the fracture severity: the amount of energy involved in fracturing a bone (i.e., the fracture energy) and the amount of articular surface involvement. It has been demonstrated in fractures of the tibial pilon that these fracture severity metrics significantly correlate with PTOA incidence.[14–16] This provides a possible explanation for differences found in the rates of PTOA development in tibial pilon and plateau fractures; that is, greater energy is absorbed or articular surface involved in creating tibial pilon fractures compared to plateau fractures.

In this study, an objective CT-based methodology for measuring fracture energy and articular surface involvement was used to explore the hypothesis that fracture severity metrics are higher in pilon fractures compared to plateau fractures. In addition, we assessed the relationship between the fracture severity measures and traditional categorical fracture classification systems to determine how well the classifications reflected severity.

METHODS

Fellowship-trained orthopedic trauma surgeons enrolled 75 patients with tibial plateau fractures spanning an entire spectrum of severity in this multi-institutional level III diagnostic study. These were compared with 52 patients having sustained tibial pilon fractures, enrolled in a similar manner. An Institutional Review Board approved use of the patient data, collected during standard-of-care clinical treatment.

Fracture severities were calculated using a previously validated, objective, CT-based image analysis methodology.[15,17]

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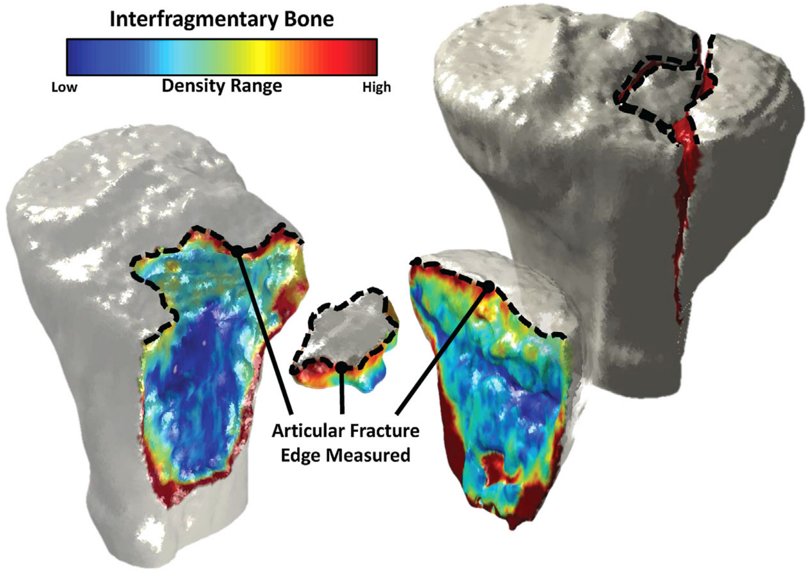

Figure 1. Custom-written software was used to measure surface area of pre-injury cortical and subchondral bone surfaces and post-injury-exposed interfragmentary bone surfaces. The fracture-liberated surface area and the bone densities across that surface were used to calculate fracture energy. The length of the edge between the subchondral and interfragmentary bone surfaces (the articular fracture edge length—highlighted with dashed black lines) was used to quantify articular surface involvement.

This technique quantifies fracture energy based upon measurement of the fracture-liberated surface area, accounting for variations in bone density over the interfragmentary surfaces (Fig. 1). Software, custom-written in MATLAB (MathWorks, Inc., Natick, MA), was used to identify all fracture fragments working from CT scan data. The surfaces of the fragments were then classified as intact cortical, subchondral, or de novo interfragmentary based upon their CT intensities and local geometric character (surface roughness, curvatures, etc.). The surface classifications were then manually evaluated and modified as needed by an expert analyst (Fig. 1). The interfragmentary surface areas of all of the fracture fragments were then summed to provide a measure of the fracture-liberated surface area. Bone densities were estimated from the CT Hounsfield intensities at each CT scan pixel using previously established relationships.[18,19] The location-specific bone density was then used to appropriately scale fracture-liberated surface areas by density-dependent energy release rates to obtain the fracture energy.[15–17] An additional measure reflecting the amount of articular surface involvement was derived by quantifying the articular fracture edge length, defined as the length of the edge at the intersection between interfragmentary and subchondral bone surfaces.

Fracture energies and articular fracture edge lengths were obtained for all pilon and plateau fractures enrolled in the study. A *t*-test statistic was used to test the hypothesis that the fracture severity characteristics differed between the two fracture locations. In order to gain further insight regarding any differences in the two fracture types, cases of similar fracture energies were qualitatively evaluated for energies at the low end, at an intermediate value, and at the high end of the fractures studied.

The fractures were also characterized using two different fracture classification systems, based upon consensus evaluation by three fellowship-trained orthopedic traumatologists (LBK, TOM, JLM). The Schatzker classification system was developed as a method for identifying groups of tibial plateau fractures with distinct pathomechanical and etiological factors.[20] This system has well-established clinical utility in guiding treatments and predicting outcomes.[21] The AO/OTA classification system, on the other hand, seeks to categorize fractures based upon their morphological characteristics in order of increasing complexity and severity, where severity "implies anticipated difficulties of treatment, the likely complications, and the prognosis."[22–24] Where the Schatzker classification seeks to categorize intra-articular fractures of the tibial plateau alone, the AO/OTA classification system is applicable to a broader set of fractures. The fracture energies computed for fractures in different Schatzker and AO/OTA classes were compared to test how well the classification systems reflected severity.

RESULTS

The range of fracture energies measured for tibial plateau fractures was 3.2–33.2 Joules (J). The range of fracture energies for pilon fractures was 3.6–32.2 J (Fig. 2a). The fracture energies (mean $\pm$ standard deviation) of the plateau fractures were 13.3 ± 6.8 J, and they were 14.9 ± 7.1 J for the pilon fractures. The distribution of energies for each fracture type was similar. Although these types of fractures are highly idiosyncratic, the smallest fragments in the plateau fractures tended to be smaller than those in the pilon fractures.

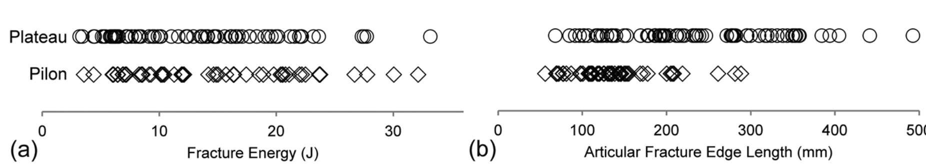

Figure 2. Tibial plateau and pilon (a) fracture energy and (b) articular fracture edge length values distributed over a full spectrum of injury severity.

The range of articular fracture edge lengths measured for tibial plateau fractures was 68.0–493.0 mm. The range of articular fracture edge lengths for pilon fractures was 56.1–288.6 mm (Fig. 2b). The articular fracture edge lengths (mean ± standard deviation) of the plateau fractures were 231.4 ± 94.7 mm, and they were 138.1 ± 54.9 mm for the pilon fractures. Fractures of the tibial plateau had greater articular fracture edge lengths than those of the pilon ($p < 0.001$).

Qualitative comparisons of tibial plateau and pilon fractures with low, intermediate, and high fracture energies showed similarities in the number and size of the fragments in each range and supported the observations regarding the amount of articular surface involvement (Fig. 3). The lower energy fractures were selected at 3.2 J and 3.6 J for the plateau and pilon, respectively. The lower energy pilon fracture had two fragments, while the lower energy plateau fracture had three. The largest two fragments on each were similar in size between the plateau and pilon, while the third fragment seen on the plateau was much smaller. The intermediate energy fractures were selected at 14.2 J and 14.9 J for the plateau and pilon, respectively. Again, similar quantities and sizes of fragments were found for the two different anatomical sites. Finally, the higher energy fractures were selected at 27.3 J and 24.6 J for the plateau and pilon, respectively. These higher energy fractures had numerous smaller fragments and involved substantial diaphyseal extension.

Fracture classifications for the plateau injuries ranged from Schatzker I to VI (Table 1). The plateau fractures ranged in AO/OTA class from 41-B1 to 41-C3 and the pilon fractures ranged from 43-B1 to 43-C3 (Table 2). The average fracture energies and articular fracture edge lengths for the most part increased with increasing Schatzker (Fig. 4) and AO/OTA classification (Fig. 5), indicating general agreement between the fracture classes and the severity metrics associated with such fractures. However, the severity metrics varied, in some instances considerably, within individual classes. In addition to the overall fracture

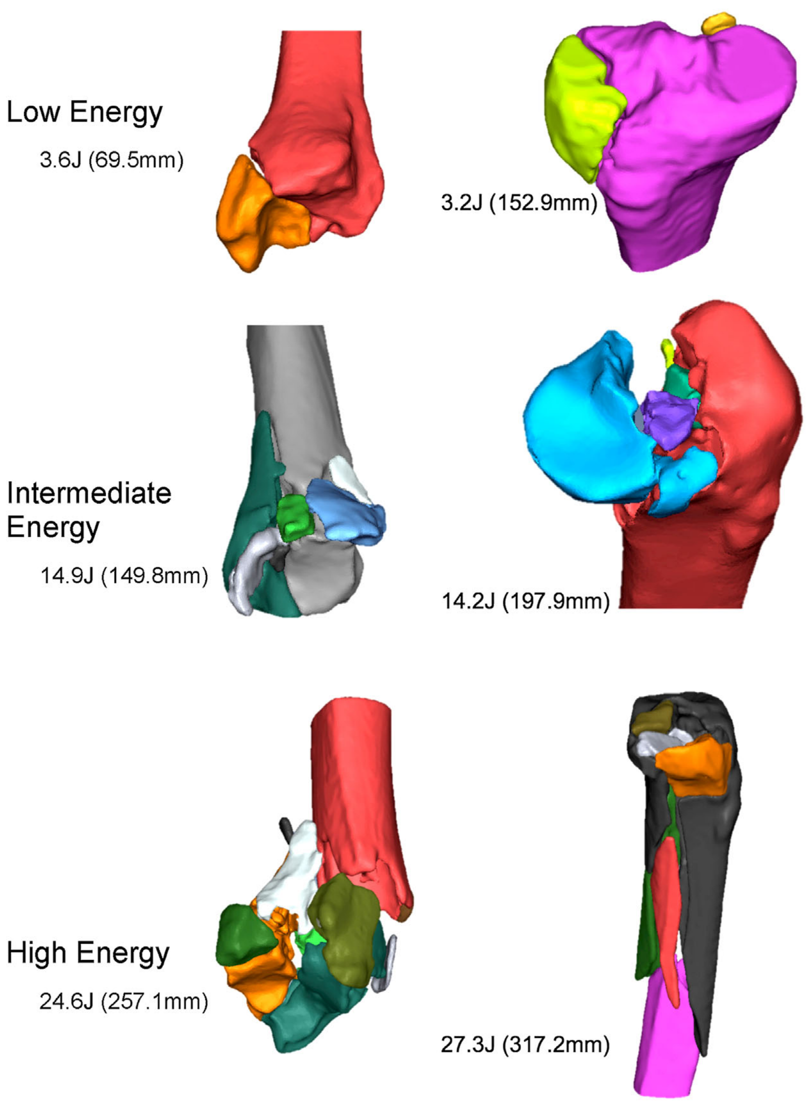

Figure 3. Fracture energy comparison between tibial pilon (left) and plateau (right) injuries. Different colors are assigned to individual fragments in these graphical representations. Articular fracture edge length values are shown for reference, in parentheses.

Table 1. Distribution of Tibial Plateau Fractures, Fracture Energies, and Articular Fracture Edge Lengths by Schatzker Fracture Classification

Schatzker Class	Number of Cases	% of Total	Fracture Energy (J)	Articular Fracture Edge Length (mm)
I	3	4	9.3 (6.9)	134.6 (40.7)
II	27	36	8.8 (4.2)	227.7 (83.0)
III	0	0	—	—
IV	16	21	11.9 (4.8)	225.3 (92.3)
V	5	7	13.7 (3.0)	247.8 (129.9)
VI	24	32	19.8 (6.1)	253.6 (110.8)

Values are mean (standard deviation).

energies of pilons and plateaus being similar, the ranges and medians of fracture energies for AO/OTA B3 and C3 fractures of pilons and plateaus were also quite similar. The same was not true of articular fracture edge lengths, with the ranges and medians of pilons being substantially smaller than those of plateaus. Finally, the higher fracture classes consistently demonstrated a wider range of fracture severity metric values than was observed for less complex fracture patterns, although there were relatively fewer fractures seen in the less complex categories.

DISCUSSION

There were no differences in the fracture energies between the pilon and plateau fracture types, but there were differences in the articular fracture edge lengths. Similar injury mechanisms typically lead to these two fractures, and previous studies show a substantially lower incidence of PTOA resulting from tibial plateau fractures compared to pilon fractures. PTOA represents an organ-level injury response that is complex and likely joint-specific. Impact tolerance of the proximal tibia may be explained by differences in joint morphology/anatomy, cartilage thickness, the subchondral bone, inflammatory response after injury, mechanics of joint load distribution, or a variety of other factors.

Differences in size and joint morphology between the tibial plateau and pilon provide possible explanations for differences in PTOA risk. This is consistent with the greater amount of articular surface involvement and comminution seen in the tibial plateau fractures, although greater surface involvement would generally be expected to increase PTOA risk. Another anatomical confounder could stem from the large difference in the size of the articular surfaces between the two joints. The tibial plateau has a significantly larger articulating surface ($\sim$1,200 mm^2) than the tibial pilon ($\sim$600 mm^2).[24,25] The tibio-talar joint could therefore experience a higher energy per unit area transmitted upon fracturing than the tibio-femoral joint. The higher energy per unit area could result in a larger degree of acute chondrocyte damage or death in the pilon when compared to the plateau. This presents an area for future development of the fracture severity measure to include bone or fracture-specific characteristics.

Substantial differences in soft tissue structures could also contribute in multiple ways. The tibial plateau has a dense, load-bearing, fibrocartilaginous meniscus and other substantial soft tissues. It is reasonable to assume that in contrast with the robust bony load bearing in the ankle, the soft tissue support in the knee may aid in preventing post-fracture deterioration, despite similar energies involved in the injuries. Further confounding this possibility is variable/occult comorbidity to these soft tissues associated with fractures of the tibial plateau. Previous studies have demonstrated approximately double the incidence of PTOA of the knee in plateau fractures with meniscectomies compared to those where the meniscus was reconstructed (74% vs. 37%).[26] In the context of surgical fracture reduction, the integrity of the soft tissues around the joint is seldom a focus of attention. Finally, the appeal of using fracture energy to assess severity in this context is that it is an indirect indicator of injury to the articular cartilage, as well as the bone. Ideally, a measure of fracture severity reflects the amount and the distribution of energy transmitted across the articular surface. The larger

Table 2. Distribution of Fracture Energies and Articular Fracture Edge Lengths for Tibial Plateau and Pilon Fractures by AO/OTA Fracture Classification

	Plateau				Pilon			
AO/OTA Class	Number of Cases	% of Total	Fracture Energy (J)	Articular Fracture Edge Length (mm)	Number of Cases	% of Total	Fracture Energy (J)	Articular Fracture Edge Length (mm)
B1	4	5	8.6 (5.8)	134.5 (33.2)	5	10	7.1 (2.2)	94.4 (26.8)
B2	2	3	16.9 (4.6)	299.8 (120.1)	1	2	6.1 (–)	120.6 (–)
B3	45	60	10.1 (4.4)	227.9 (88.3)	15	29	10.2 (5.0)	127.1 (38.5)
C1	2	3	21.4 (0.3)	140.8 (79.1)	2	4	17.5 (14.6)	99.6 (1.4)
C2	5	7	17.5 (7.6)	220.1 (100.5)	12	23	19.7 (6.3)	124.1 (61.0)
C3	17	23	20.3 (6.0)	276.7 (110.6)	17	33	18.1 (5.1)	169.1 (52.8)

Values are mean (standard deviation).

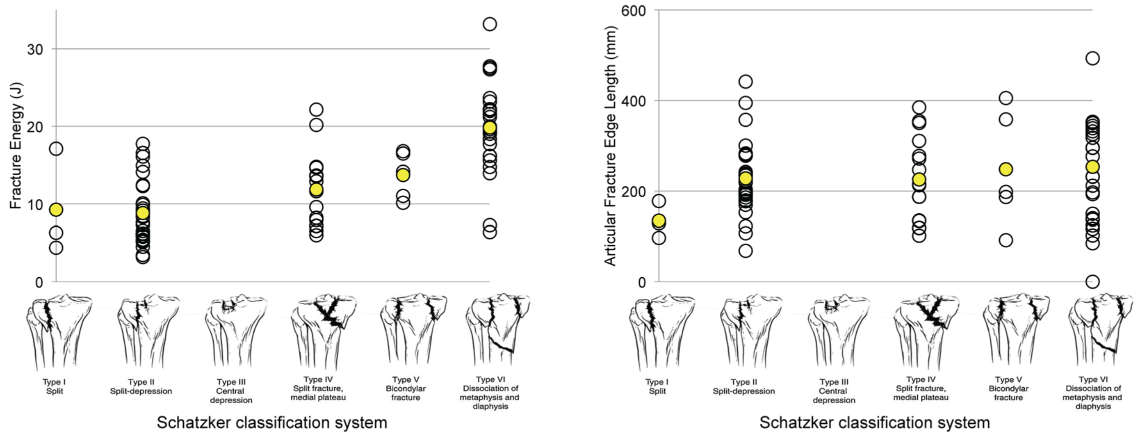

Figure 4. Range of fracture energies and articular fracture edge lengths as they vary over the Schatzker classes of tibial plateau fractures.

the quantity of energy, the more initial cartilage damage and subsequent degeneration would be predicted. Other joint-specific factors influential in this respect include the cartilage thickness and the rigidity of the subchondral and underlying metaphyseal bone. The cartilage of the tibial plateau is significantly thicker (~3 mm) than for the tibial pilon (~1.5 mm). The intra-tissue strains at the time of injury would therefore be expected to be more severe in the thinner cartilage of the pilon compared to the plateau.

The larger range of fracture energies seen in higher classes of the fracture classifications (C3, Schatzker V and VI) may reflect the fact that more complex and variable injuries make up these classes. However, the higher class fracture patterns were not necessarily more severe (i.e., did not always have higher fracture energies). This suggests that fracture classifications are less reflective of severity for the more complex fracture patterns. A surprisingly wide range of fracture energy was seen for the fracture classifications that we assessed, suggesting that these classifications are not a reliable surrogate for fracture severity. Combining fracture classification, which categorizes the morphologic characteristics of the fracture, with objective measurement of fracture energy would provide a more complete assessment of articular fractures.

Historically, studies comparing different groups of fractures have used AO/OTA fracture classification to show that the groups had similar fracture characteristics and severity. Perhaps the most useful conclusion from these data is that prior studies failing to demonstrate group equivalence simply by showing no statistical difference in fracture classification type are missing critical information about underlying differences in fracture severity. Assigning "high energy" and "low energy" based on injury mechanism and fracture pattern is largely subjective and fails to sufficiently stratify severity. The data presented in this study provide strong evidence of the utility that fracture energy has in the context of clinical research.

This study is not without limitations. The accuracy of the fracture energy calculations may suffer either

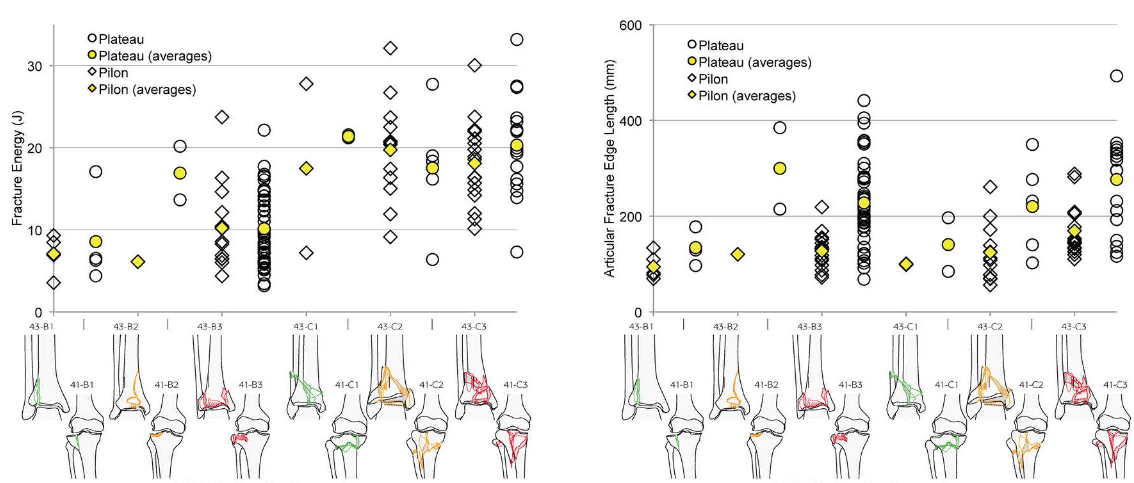

Figure 5. Range of fracture energies and articular fracture edge lengths as they vary over the different AO/OTA classes for the tibial plateau and pilon fractures.

when small bone fragments are missed in segmentation from CT or when there is substantial compaction of bone. The volumes of the smallest fragments segmented were on the order of 10–20 mm^3. We cannot rule out inaccuracies associated with missing smaller fragments but would not expect for those to contribute appreciably to fracture energy absorption. Bone compaction was not assessed in our measurements but again, given the relatively low density of cancellous bone subject to compaction, it is unlikely that this would introduce substantial inaccuracy. Another limitation is that soft tissue status was not available for inclusion in the assessments of fracture severity. Ultimately, a more robust predictive algorithm may involve not only calculation of fracture energy but also some measure of soft tissue status. A present lack of follow-up data prevented the evaluation of the relationships between fracture severity and outcomes in the plateau and pilon fractures. Establishing these relationships is the objective of ongoing study in these patients, who are all being followed prospectively.

PTOA is a complex disease with many contributing factors. The findings in this study disprove our hypothesis that tibial pilon fractures have a higher energy absorbed than plateau fractures across the spectrum of injury, but they raise new questions about differences in the amount of articular surface involvement. Our results show similar energy absorption profiles with greater articular involvement in the tibial plateau, suggesting that it may be more tolerant of impact injury compared to the distal tibia. This possibility will need to be tested further as longer term outcome data become available for the specific patients analyzed in this study.

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AUTHORS' CONTRIBUTIONS

All authors made substantial contributions to the research design, data acquisition, and analysis/interpretation of data. K.D., L.K., T.M., J.L.M., and D.D.A. were involved in the drafting of the paper, and all authors provided subsequent critical review. All authors have read and approved the final submitted manuscript.

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An objective CT-based method for quantifying articular fracture severity : clinical application in multiple joints

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AN OBJECTIVE CT-BASED METHOD FOR QUANTIFYING ARTICULAR FRACTURE SEVERITY: CLINICAL APPLICATION IN MULTIPLE JOINTS

by

Kevin Nathaniel Dibbern

A thesis submitted in partial fulfillment
of the requirements for the Master of Science
degree in Biomedical Engineering in the
Graduate College of
The University of Iowa

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CERTIFICATE OF APPROVAL

MASTER'S THESIS

This is to certify that the Master's thesis of

Kevin Nathaniel Dibbern

has been approved by the Examining Committee for
the thesis requirement for the Master of Science degree
in Biomedical Engineering at the December 2015 graduation.

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ABSTRACT

Adequately assessing injury severity is critical in treating articular fractures. Severity assessment is used to inform clinical and surgical decision making through anticipation of patient outcomes. The assessments generally involve interpreting radiographs or CT image data. In recognition of the poor reliability of existing clinical severity assessments, objective severity metrics have been developed that are firmly rooted in mechanics and provide capable alternatives for use in research, where reliable data is paramount. Their broader clinical utility remains to be established.

An existing CT-based method for determining the energy expended in a bone fracture was extended to facilitate its use in more fracture types. Its utility in different articular joints was evaluated. Specifically, the severities of articular fractures of the proximal tibia (plateau), of the distal tibia (plafond), and of the calcaneus were compared with present clinical severity metrics, patient outcomes, and/or surgeon rankings of severity. Differences in the fracture energies in the different joints were also compared.

The objective fracture energy metric compared favorably with present clinical severity metrics. The fracture energies for fractures of the tibial plateau had between 71% and 78% concordance with surgeon rankings of severity. The calcaneal fracture energies had a 75% concordance with the present clinical standard. Fracture energy was also predictive of later radiographic indicators of post-traumatic osteoarthritis.

The fracture energy metric is a capable tool for analyzing fracture severity in various joints. Fracture energy correlated well with outcomes and present clinical gold standards for severity assessment. The methods for assessing fracture energy described are highly useful for orthopaedic research and have potential as an important clinical tool.

PUBLIC ABSTRACT

Adequately assessing injury severity is critical in treating articular fractures. Severity assessment is used to guide clinical and surgical decision making through anticipation of clinical outcomes. The assessments generally involve interpreting medical image data. The poor reliability of existing clinical severity assessments led to the development of objective severity metrics that have proven capable alternatives for use in research, where reliable data is paramount.

A new means for measuring the energy expended in fractures was developed for objectively assessing injury severity. Its capability in different anatomical regions was evaluated. Specifically, it was compared with present clinical metrics, patient outcomes, and/or surgeon rankings of injury severity in the knee, ankle, and in the calcaneus. The different distributions of fracture energies in these different regions were also compared.

The objective fracture energy metric compared favorably with present clinical metrics. The fracture energy metric in the tibial plateau had between 71% and 78% concordance with surgeon rankings of severity. The calcaneal fractures analyzed had a 75% concordance with the present clinical standard. The fracture energy was also predictive of later development of post-traumatic osteoarthritis.

The fracture energy metric is a capable tool for analyzing injury severity in various joints. This utility had previously been shown in fractures of the tibial plafond, but improvements have allowed for extension to other joints and bones. The resulting severity metric shows good correlation with outcomes and present clinical gold standards for severity assessment. The methods for assessing fracture energy developed are highly useful for orthopaedic research and have potential to be an important clinical tool.

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CHAPTER 1: INTRODUCTION AND BACKGROUND

1.1 Fracture severity assessment and its significance

Adequately assessing injury severity is critical in treating fractures of articular joints. Severity assessment informs clinical and surgical decision making by enabling the prediction of patient outcomes. In the case of articular fractures, the risk of later post-traumatic osteoarthritis (see §1.2 below) is a major concern. Reliable injury severity assessment is necessary for meaningful comparisons of different treatment options. For these reasons, among others, the poor reliability of existing clinical severity assessments led to the development of objective fracture severity metrics that have proven capable alternatives for use in research, where reliable data are paramount[3-8].

Fractures are classified using different schemes in orthopaedics to convey information about them. The most useful clinical fracture classifications are largely based on categorizing injuries according to various features of articular fractures that are readily identifiable on radiographs or CT scans. Typically these features include: the location of the fractures, the number of fragments, the amount of fracture displacement, and the anticipated degree of surgical difficulty in treating them[9]. Perhaps not surprisingly, subjective assessment of these features can vary between physicians and lead to the aforementioned poor reliability. Prior methods that sought to obviate these problems focused on identifying and quantifying objective CT-based metrics of fracture severity, such as the fracture energy, the degree of articular comminution, and the amount of fracture displacement [3, 4, 10, 11]. The focus of the present work remains on quantifying the joint injury by measuring the amount of energy transmitted through the

articular surface in the fracturing of bone, but an additional aim is to broaden the clinical utility and practicality of using these methods.

Prior objective CT-based methods for obtaining these metrics succeeded in fulfilling the need for increased reliability, but they lacked broader applicability; constrained by either relying on the existence of CT scans of the intact contralateral limb or having a suitable anthropometric surrogate for the intact limb [3-5, 11]. These limitations were undesirably compounded by the sometimes abstruse nature of expedited surrogate metrics that were developed. In contrast to this, traditionally embraced fracture severity metrics have stood the test of time because of their broad applicability and ability to be easily understood. The AO classification of long bone fractures exemplifies these successes, possessing easily identifiable classification criteria and measures that can be applied and understood in any joint[9]. The goal of the present work is to extend existing methods to emulate these qualities with an objective metric that can be utilized more broadly for research and clinical application.

Accomplishing the goal of creating a more utilitarian methodology also requires that the metric be fairly expedient and simple to use. This thesis aims to incorporate the broad applicability and plain features that have been staples of widely adopted clinical fracture classification systems while improving upon their reliability. A major benefit of the methods proposed herein is that they use measures of a physically meaningful concept; the quantity of energy absorbed by bone in fracture production. This aids researchers in the understanding and interpretation of severity results and is important as it can be difficult to assess the quality of a newly developed metric. The challenge of assessing the new metric, lacking any other gold standards with which to compare, was

undertaken by analyzing results alongside previously validated fracture energy measures and the present clinical gold standard of surgeon opinion. Expediting assessment methods that produce direct measures of fracture severity was achieved by implementing a trained machine learning classifier to enable the automated identification of and provide more accurate discrimination of fractured bone surfaces working from segmentations. In addition, a 3d graphical user interface was developed to finalize the identification of de novo fracture surface in bone models segmented from CT scans.

This thesis details the development of a fracture severity assessment methodology that is capable of being applied to any articular fracture. It addresses prior issues with reliability, utility, and clarity by proposing an objective CT-based method to quantify fracture liberated surface area and to determine the quantity of energy absorbed by the bone in producing a fracture. This study opens the possibilities for use of such a robust, expeditious, and versatile metric in a diverse set of research and clinical applications where objective assessment of injury severity is required.

1.2 Post-Traumatic Osteoarthritis:

Post-traumatic osteoarthritis (PTOA) is a debilitating, degenerative condition of the joints that follows a traumatic injury. It is most common and likely following a fracture involving a joint. PTOA results in impairment equivalent to that of end stage renal disease or heart failure, and it affects a large percentage of those who have suffered significant joint injuries[12]. With present care, 44% of patients having sustained an intra-articular proximal tibia (plateau) fracture will develop knee OA, while greater than 50% of those with intra-articular distal tibia (plafond) fractures will develop OA[13]. By five to eleven years after a tibial plafond fracture, the incidence of ankle OA is 74%. [14] While the understanding of the etiology of PTOA has improved in recent years, patient-specific prognoses are, however, still "largely speculative."[15]

The extent of damage to the joint and the likelihood that the joint will later develop PTOA following a joint injury is, at least in part, a function of the initial mechanical insult to the articular surface. As insult severity varies and strongly influences the probability of PTOA development, different injury severities necessitate different treatment options. For example, in more severe injuries, a primary fusion or arthroplasty could spare the patient future surgeries, because the joint would be expected to rapidly develop PTOA regardless of surgical intervention. Presently, fracture classification systems fill the role of guiding surgical management in such situations. While these classifications are currently the standard of care, clinical decision making could be further improved with an objective fracture severity metric that could be expeditiously and easily obtained for a variety of fracture types.[15-17]

1.3 The Tibia:

As previously detailed, the ability to better predict the onset of PTOA is of particular import in the assessment of fracture to an articular surface. An objective CT-based fracture severity metric was previously shown to improve such predictions in the distal tibia [10]. The CT-based methodologies proposed herein would expand use to the proximal tibia, among other joints, in pursuit of application to any articular fracture. The tibia articulates proximally with the femur to form the knee joint and distally with the talus to form the ankle joint. Fractures through the proximal and distal articulating surfaces of the tibia can be particularly devastating injuries that are predisposed to PTOA and joint degeneration. Therefore, enhanced predictive capabilities regarding injury outcomes involving these joints would have a significant impact on patient care.

1.3.1 Anatomy of the Knee Joint:

The proximal portion of the tibia, often referred to as the tibial plateau, comprises the distal-most portion of the knee joint. The knee is the weight-bearing joint most often affected by OA[18]. It consists of two bony articulations: the patellofemoral joint and the tibiofemoral joint. The tibiofemoral joint is the primary weight-bearing joint in standing, knee flexion, and normal gait. The two condyles of the distal femur articulate with two distinct surfaces on the tibial plateau, separated into medial and lateral compartments by a bony protrusion known as the tibial spine. The medial compartment has the largest contact area and typically carries the larger load. The lateral compartment is shallower and possesses less bony stability, relying instead on the substantial soft tissue structures of the knee for stability [18, 19].

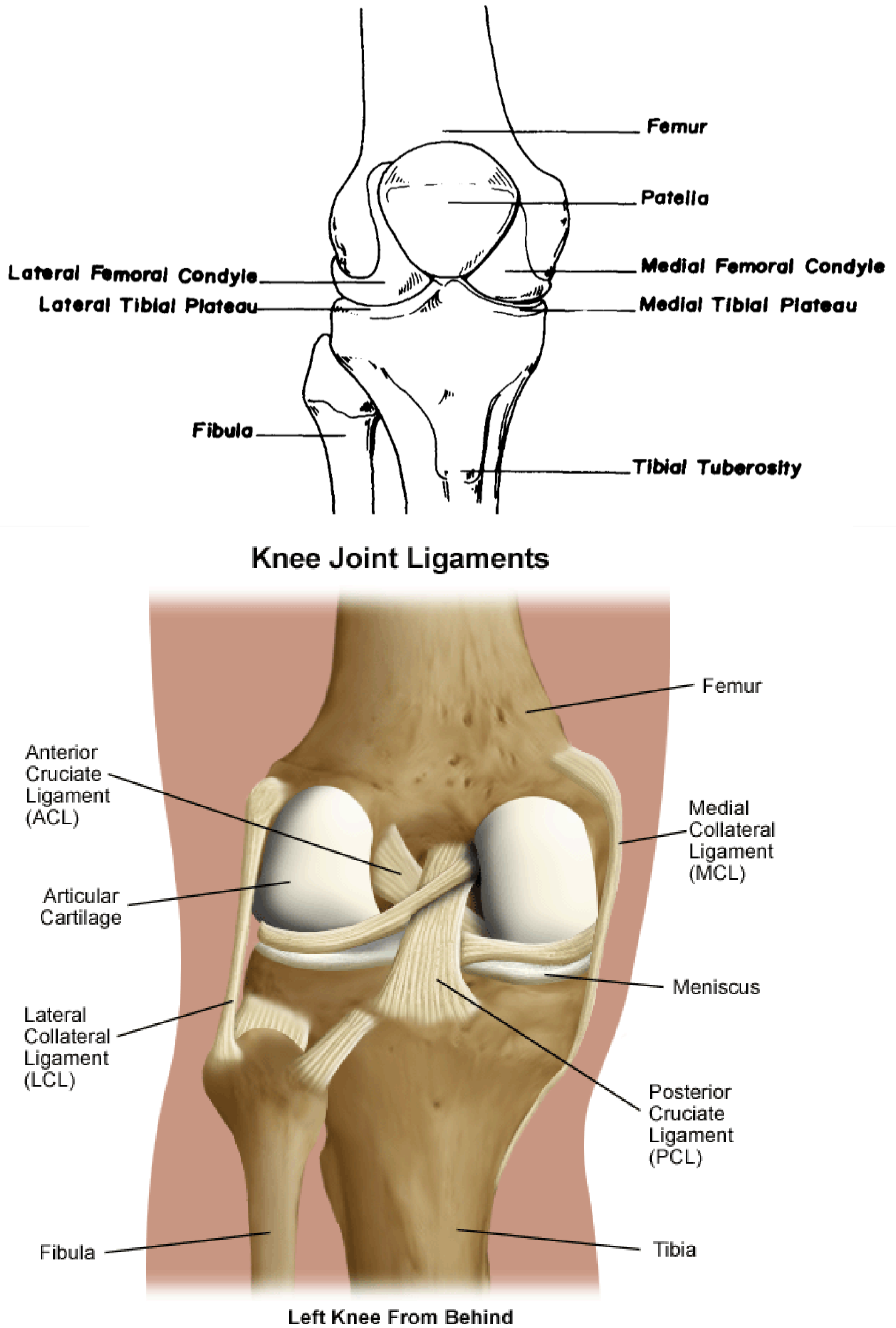


Figure 1-1: Anatomy of the proximal tibia [20, 21].

The soft tissues relied upon for stability in the knee include a fibrocartilaginous meniscus, five strong ligaments, and the patellofemoral contact. The anterior cruciate, posterior cruciate, medial collateral, and lateral collateral ligaments all restrain motion to prevent excessive translation of the tibia. These ligaments attach to the tibia as shown in Figure 1-1. The popliteofibular ligament (not labeled) resists posterolateral rotation of the tibia with respect to the femur adding to the soft tissue constraints afforded by the other ligaments. The meniscus contributes a substantial portion of load carriage across the joint, and damage to it or any of the surrounding soft tissue structures can be a significant factor in OA development [20, 22].

1.3.2 Anatomy of the Ankle Joint:

The ankle is comprised of the distal portions of the tibia and fibula articulating over the talus. The distal portion of the tibia is often referred to as the tibial plafond (or, interchangeably, the tibial pilon). Plafond, the French word for ceiling, is typically used to describe a vaulted or domed structure. Anatomically, this refers to the “dome” made over the talus by the distal tibia, its medial malleolus protrusion, and the fibula on the lateral side. In contrast with the knee, this bony anatomy makes a robust construct for articulation without requiring much contribution from the associated soft tissues.

The tibiofibular ligament, forming the syndesmosis joint, is the most important soft tissue structure in the ankle. It constrains the fibula relative to the tibia to create the proximal-most portion of what is effectively a mortise and tenon joint (as seen in Figure 1-2). Additional ligamentous stability is afforded by the four robust ligamentous structures encapsulating the joint.

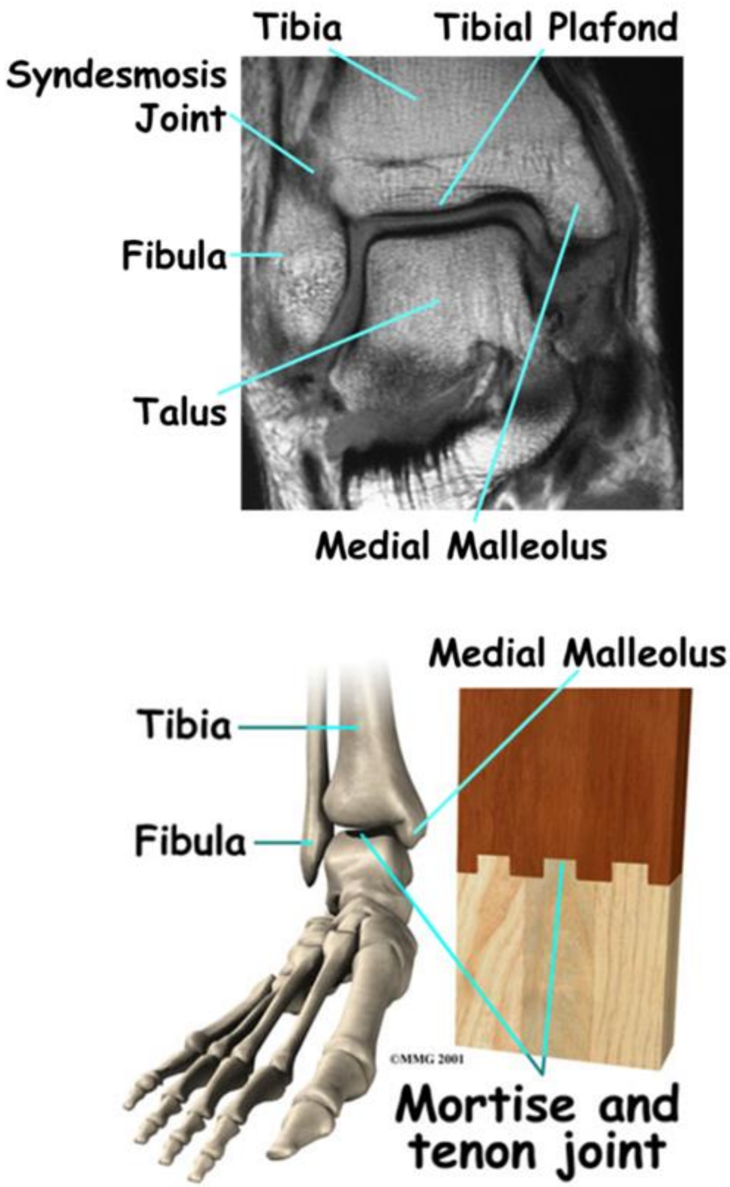


Figure 1-2: Anatomy of the Distal Tibia
[Rosenberg, Z.S., J. Beltran, and J.T. Bencardino, *From the RSNA refresher courses - MR imaging of the ankle and foot.* Radiographics, 2000. 20: p. S153-S179.]

1.3.3 Tibial Plateau Fractures

1.3.3.1 Description

Fractures of the tibial plateau are relatively uncommon, representing approximately 1% of all fractures. The circumstances that cause these fractures can vary greatly in the energy involved and the mechanism, ranging from higher-energy motor vehicle accidents, mechanical falls (not due to fainting or seizure), and sports injuries to lower-energy mechanisms in osteoporotic bone. Fractures are typically caused by a varus or valgus force combined with an axial loading. This force typically results in impaction or cleavage of the lateral or medial plateau. As the medial plateau is larger and typically stronger than the lateral plateau, fractures are more commonly found in the lateral plateau (55-70% of total incidence). Although rarer, fractures of the medial plateau (10-23% of total incidence) and of both plateaus (10-30% of total incidence) are considered to be higher-energy and more severe injuries.[22]

Outcomes of tibial plateau fractures have been shown to be largely dictated by initial injury severity, as judged by clinical classification systems[23]. Another important factor in these outcomes is the degree of ligamentous instability and the damage to the meniscus,[22] two factors that are beyond the scope of the current work.

1.3.3.2 Classification

The Schatzker and AO/OTA classification systems are the most commonly utilized for classifying fractures of the proximal tibia. The Schatzker classification system (Figure 1-3) was developed as a method for identifying groups of fractures with distinct pathomechanical and etiological factors[24]. This system has well established clinical

utility in guiding treatments and predicting outcomes[25]. The AO/OTA classification system (Figure 1-4), on the other hand, seeks to categorize fractures based upon their morphological characteristics in order of increasing severity, where severity "implies anticipated difficulties of treatment, the likely complications, and the prognosis."[9, 26] Where the Schatzker classification seeks to categorize intra-articular fractures, the AO/OTA Classification system encompasses a broader set of fractures.

The AO/OTA classification consists of: Type A, nonarticular fractures; Type B, partial articular fractures; and Type C, complete articular fractures. These are further subdivided, as shown in Figure 1-4, by increasing severity into subtypes 1, 2, and 3.The Schatzker classification, shown in Figure 1-3, consists of six categories denoted I-VI: class I fractures are lateral split type fractures without depression; class II fractures have a lateral split with depression; class III fractures are central depression fractures; class IV fractures are split medial plateau fractures; class V fractures are bicondylar in nature; and class VI are bicondylar with metadiaphyseal extension.

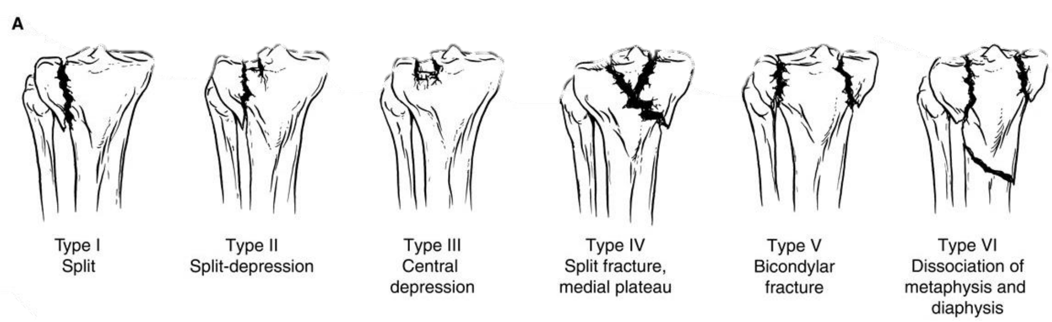


Figure 1-3: Schatzker Classification of Tibial Plateau Fractures. Developed to identify and group fractures with distinct pathomechanical and etiological factors, its ordering from Type I to Type VI reflects injuries that are increasingly challenging to treat. [27]

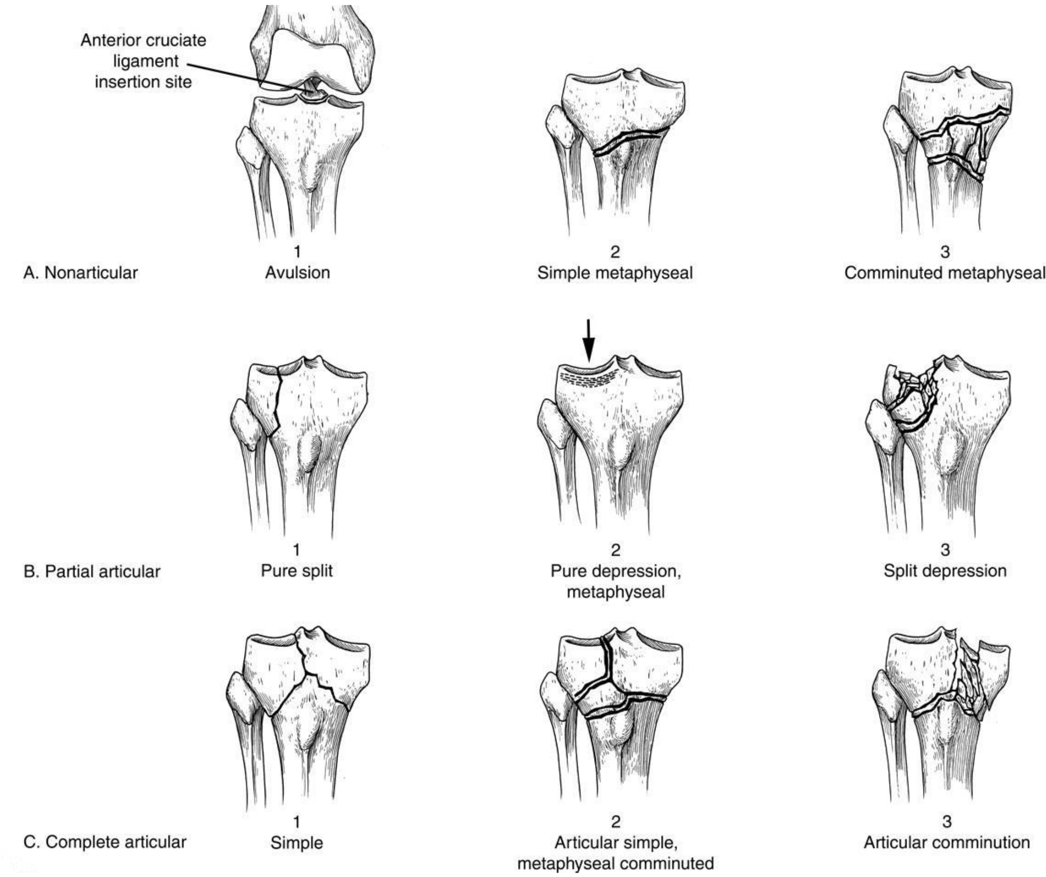


Figure 1-4: AO/OTA Classification of Tibial Plateau Fractures. It was created as a means for standardizing descriptions of fractures for research and communication. [27]

1.3.4 Tibial Plafond Fractures

1.3.4.1 Description

Fractures of the plafond are rare injuries representing less than 1 percent of lower extremity fractures and only 3-10% of tibial fractures[28-31]. Despite their rarity, they represent some of the most difficult fractures in the lower extremity to treat and are often associated with a high degree of soft tissue injury. There are typically two types of plafond injury: those arising from large axial impact forces, and those arising from torsional forces. The axial impact injuries occur when the talus is driven into the tibial plafond initiating a fracture pattern that extends from the plafond up the tibial shaft. These types of forces can stem from high energy falls from height, motor vehicle collisions, and other axially compressive injuries. The torsional type of fracture can produce less-complex, lower energy patterns that have large bone fragments and minimal impaction. In contrast, high energy compression injuries can have many smaller fragments known clinically as severe comminution, impaction of these and larger fragments, as well as damage to articular cartilage. Energy is often anecdotally related to injury severity due to these relationships between energy and bone fragment size, as larger fragments resulting from lower energy fractures are often easier to reduce with fracture fixation hardware. As the quality of surgical reduction is likely to increase with these improved methods, so are patient outcomes as the severity of the injury sustained and the quality of articular reduction assessed by orthopaedic surgeons have been found to be strongly correlated with PTOA [32].

This establishes a major component of the relationship between fracture energy, clinical injury severity assessment, and patient outcomes. It also serves to demonstrate

why plafond fractures are of particular import to the study of severity assessments as they can be used as predictive landmarks with which capabilities can be measured.

1.3.4.2 Classifications

There are two commonly utilized fracture classification systems in the distal tibia: the AO/OTA classification and the Ruedi-Allgower system. The AO/OTA classification (figure 1-5) consists of types A through C and a number, 1 through 3, reflecting increasing severity. It is a part of the larger AO/OTA classification of long bone fractures [9]. AO/OTA type A fractures are distal tibial fractures in the metaphysis without intra-articular extension. Type A1 fractures are simple, A2 fractures are comminuted, and A3 fractures are severely comminuted. Similarly, AO/OTA type B fractures are partial articular fractures categorized as B1 for pure split, B2 for split depression, and B3 for depression with multiple fragments. AO/OTA type C fractures involve the whole joint surface, with C1 being a simple split going through the metaphysis, C2 being an articular split with multiple fragments, and C3 having multiple fragments of the articular surface and metaphysis. The Ruedi-Allgower system (Figure 1-6) also subdivides the fractures into three types: type I is an intra-articular fracture without significant displacement, type II has significant displacement and minimal comminution, and type III has significant comminution as well as intra-articular displacement[26].

Both classification systems, AO/OTA and Ruedi-Allgower, stratify the range of severity effectively and have been deemed to have sufficient inter-observer reliability between major fracture types. However, at the subgroup level, both systems have exhibited poor inter-observer reliability in differentiating fracture severity[7].

Nonetheless, the opinion of an experienced traumatologist remains the gold standard for assessment of fracture severity against which any new objective measures must be gauged. The development of objective methods for assessing fracture severity would, however, enable greater inter-observer reliability and provide new opportunities for the field of orthopaedic research.

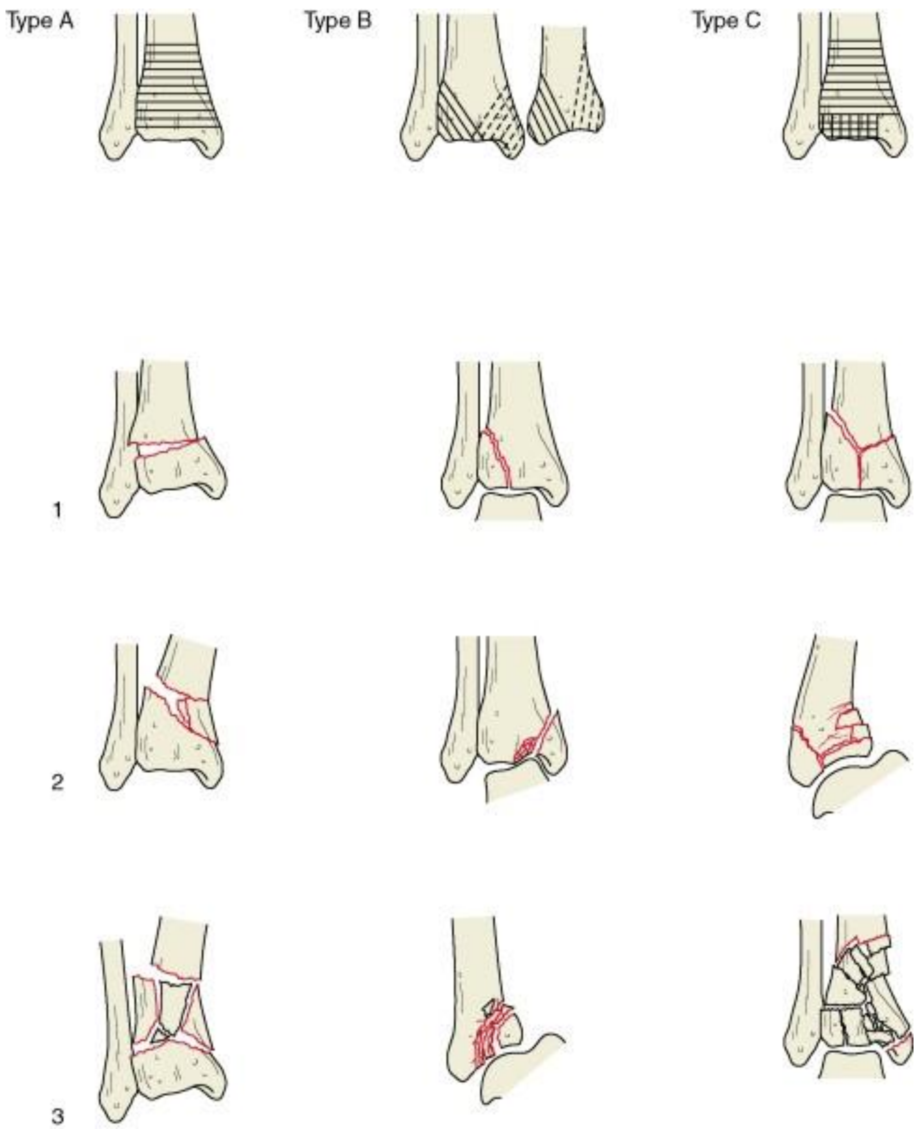


Figure 1-5: AO/OTA classification of plafond fractures.[33]

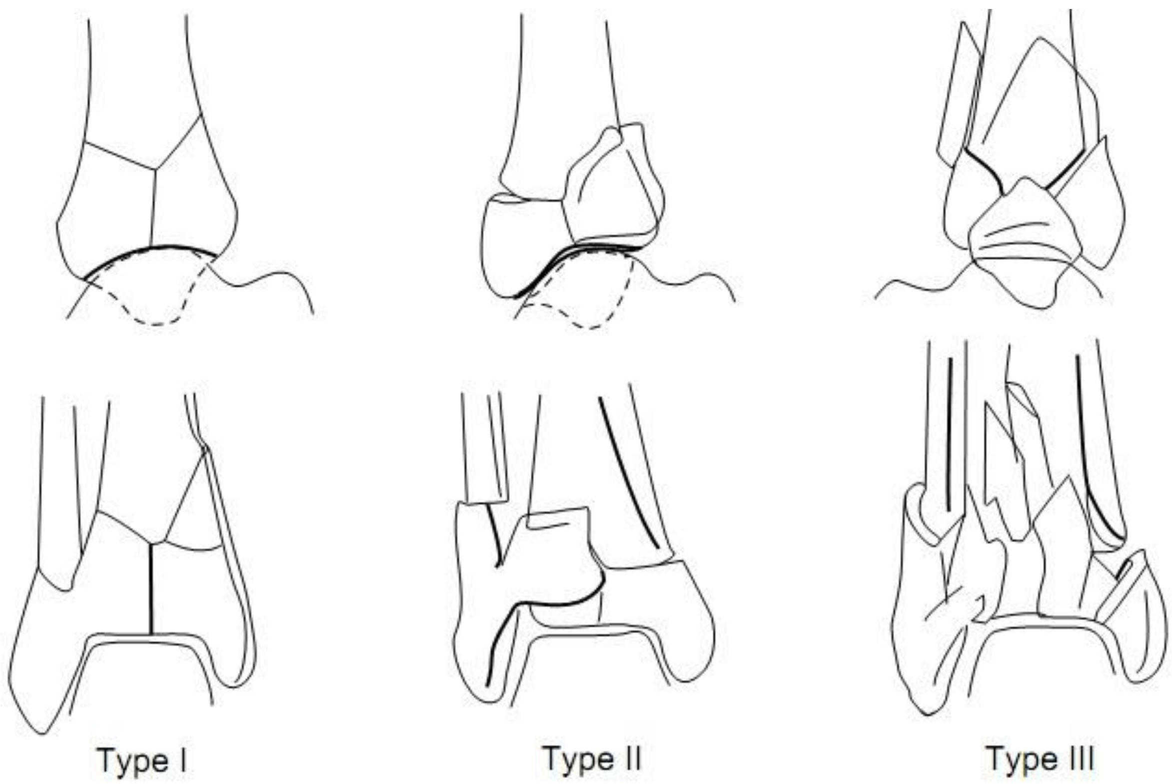


Figure 1-6: Ruedi-Allgower classification of tibial plafond fractures.[34]

1.4 The Calcaneus:

The calcaneus, or heel bone, is the largest bone in the foot and as such, is critical to normal foot function. It is capable of withstanding the high tensile, bending, and compressive forces experienced in daily life without fatiguing. The posterior half of the calcaneus constitutes the calcaneal tuberosity, a mostly cylindrical process upon which several strong tendons and ligaments attach. The anterior half of the calcaneus includes the cartilage-covered bony protuberances that comprise the subtalar and calcaneal-cuboid joints. The lateral-most aspect of the calcaneus forms the sinus tarsi. The distal-most end of the fibula extends in the lateral malleolus near this feature. The sustentaculum tali projects from the medial side of the calcaneus forming a shelf for the prominent middle facet [35].

The subtalar joint is the primary weight-bearing articulation of the calcaneus. It has three facets that articulate with the inferior talus: the anterior, middle, and posterior facets. The posterior facet is the largest and bears the majority of the subtalar joint loading. Together, the three facets allow for inversion and eversion of the foot. These motions are guided by substantial soft tissue structures surrounding the foot[36].

There are a number of critical soft tissues attached to the calcaneus. Notably, the Achilles tendon, the strongest tendon in the body, attaches the gastrocnemius, soleus, and plantaris muscles to the posterior aspect of the calcaneus. The calcaneal fibular ligament provides lateral stability to the foot and the posterior deltoid ligament provides medial support. Important to surgical reduction is the interosseous talocalcaneal ligament running just lateral to the sustentaculum tali through the canal. This strong ligament is

what makes the sustentaculum tali the "constant fragment" upon which surgeons base their reductions of fractured calcanei [35, 36].

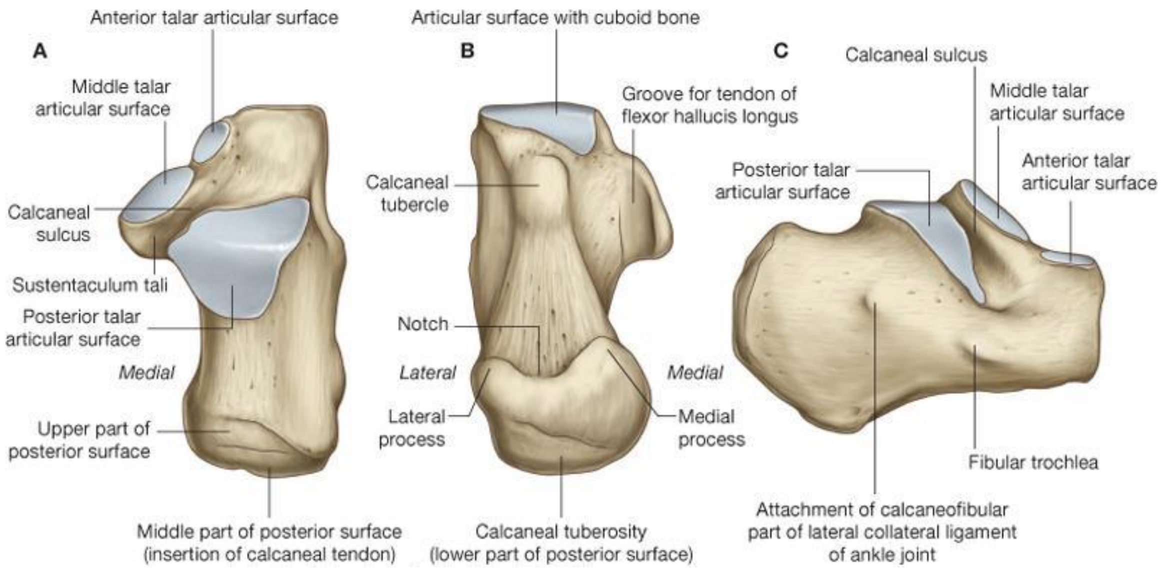


Figure 1-7: Anatomy of the calcaneus

1.4.1 Fractures of the Calcaneus

Fractures of the calcaneus constitute approximately 1-2% of all fractures; the calcaneus, however, is the most frequently fractured of the foot bones [37]. Calcaneal fractures can be minor injuries, but many are more severe, resulting from high energy mechanisms of injury like motor vehicle collisions and mechanical falls [38]. These high energy injuries often result in long healing times (up to two years) and eventual subtalar joint PTOA. Clinically, the Sanders classification system is the most commonly used for categorizing intra-articular calcaneal fractures. The Sanders classification consists of four primary types: type I – non-displaced fractures (less than 2mm displacement), type II – fractures consisting of a single intra-articular fracture dividing the posterior facet into two pieces, type III – fractures consisting of two intra-articular fractures dividing the posterior facet into three pieces, and type IV – fractures consisting of three or more intra-articular fractures. Subtypes for type II and III class fractures are defined as A for those involving the anterior calcaneus, B for those involving the middle of the calcaneus, and C, for those involving the posterior calcaneus [38-40].

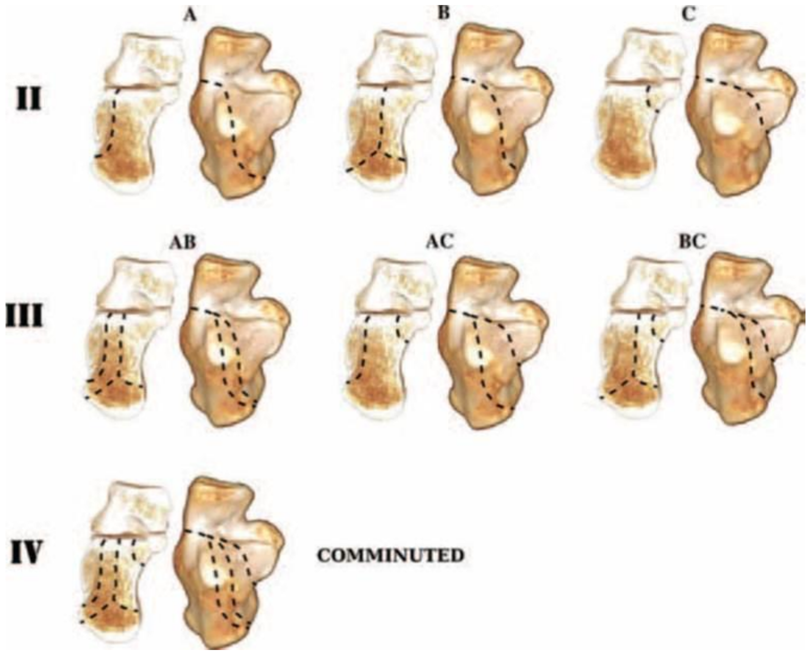


Figure 1-8: Sanders classification system for calcaneal fractures.[2]

Clinical management of these fractures involves choosing between three general treatment options: non-operative, open reduction with internal fixation, and percutaneous reduction and fixation. Non-operative care typically consists of elevation, application of ice, utilization of a splint, and early mobilization. Non-operative techniques reduce the risk of infection and other complications associated with surgery but can result in poor restoration of subtalar joint and hind-foot deformities that increase risk of PTOA development. Open reduction with internal fixation aims to restore joint congruity as accurately as possibly by directly visualizing the fracture. While this is generally considered to be the standard for reduction of the articular surface, the large wound created by the incision can be prone to infection and related complications. Percutaneous reduction techniques utilize CT scans to plan surgical approaches and provide fixation through minimally invasive incisions. The goal of this technique is to

restore articular congruity to the extent possible without the large incisions associated with ORIF techniques. At present, there is a paucity of evidence to definitively support the effectiveness of any of these techniques for all but the most severe of fractures [38].

1.5 Previous Fracture Severity Work

Acute fracture severity is considered one of the most important predictors of injury prognosis and risk of poor outcomes [10, 16]. Clinicians have utilized plain radiographs and CT to broadly classify fractures based on their locations and the relative number of fragments, but they have as yet been unable to reliably and objectively quantify severity [4, 7]. To address these problems, previous work developed an objective CT-based fracture severity metric that is capable of predicting PTOA. The original methods for obtaining fracture energy were robust but slow. Further work on an expedited objective methodology for assessing severity without directly quantifying fracture energy succeeded in reducing the time to evaluate cases from 8-10 hours down to under 15 minutes [11]. This was an important development as it moved the time required to obtain the objective metric into a clinically relevant time scale. Having the time to process a case on a clinically relevant time scale, typically under an hour, is important as it enables data to be given to the clinician while initial and definitive treatment options are being explored.

The basis of all objective fracture severity assessments is in the widely held belief among orthopaedic traumatologists that "the extent of bone, cartilage, and soft tissue damage is directly related to the energy imparted on these structures [4]." In 2002, Beardsley et al. showed that fracture mechanics theory for a brittle solid postulating a monotonic relationship between fracture surface area generation and energy absorption

could be applied to bone [41]. Utilizing CT data from fractures, the fracture surface area of bones could be discriminated and thus, the fracture energy measured. From these developments, a metric for quantifying the severity of tibial plafond injuries was developed showing excellent correlation with physician assessment of injury[5, 6, 10, 41]. To create this initial metric, important assumptions were made in the calculation of fracture energy. A number of these assumptions also apply in the context of this thesis.

One of the primary motivations for creating an assessment of severity is the determination of prognosis, in this case, the likelihood of PTOA development [10]. To more accurately predict PTOA, previously developed metrics have discounted fibular fractures to better estimate the amount of energy insult the cartilage experienced during the fracture. These assumed that any energy going through the fibula had circumvented the articular cartilage and, therefore, would not contribute to the development of PTOA[42]. Additionally, these metrics draw from the foundational fracture mechanics theory in their assumption that the material must be a brittle solid for the energy creating the fracture to have a monotonic relationship with the fracture liberated surface area. Therefore, at the high rates of loading experienced in fracture generation, bone was appropriately assumed to be a brittle solid. The reason for this relationship stems from the fact that the only way in which mechanical energy can be absorbed by these brittle solids is via the process of fracturing. These fractures create new surface area along the fractured edges; in an ideally brittle solid, this liberated surface area is directly proportional to the quantity of energy absorbed.

Ergo, a key factor in the creation of an objective fracture severity metric is the ability to measure fracture liberated surface area. In past studies, this liberated surface

area was quantified by utilizing an edge detection algorithm that found bone surfaces (edges) within two dimensional CT slice reconstructions [10, 11]. This identification of “free” bone surfaces was done without regard for whether the surface was native (i.e., existed prior to the fracture) or was inter-fragmentary (i.e., de novo bone surface liberated as part of the fracture). The bone surfaces were found both for the fractured limb and for the unfractured (intact) contralateral bone. The fracture liberated surface area was then identified by subtracting the surface area of the intact contralateral bone from the total bone surface area of the fractured limb slice by slice in the CT-image [4]. A significant amount of time (on the order of 8 to 10 hours per case) was required for completing the necessary manual interventions during this segmentation task. Therefore, while robust in the sense that manual verification of the segmentations was integral to the approach, this method had the distinct disadvantages of requiring the acquisition of an intact contralateral CT scan with which to compare surface areas and being extremely labor intensive.

Fracture energy calculations also need to account for variation in bone density, because the energy required to fracture the bone is greater for more dense bone. Following segmentation, the bone density was determined using the mean CT (Hounsfield Unit) intensities in semi-automatically identified cancellous, thin cortical, and thick cortical regions. Fracture energy calculations in this case were performed by multiplying the identified fracture liberated (de novo) surface area by the location and patient specific energy release rates for bone. One substantial improvement made upon this method is in the more robust and accurate localization of Hounsfield Unit dependent energy release rates. The method proposed in this thesis assigns the energy release rates

at each vertex along the de novo fractured bone surface rather than relying upon averaged values applied to the entire surface.

An expedited method was proposed in subsequent work to remove the requirement of an intact contralateral limb and to mitigate time consuming manual editing. The stated purpose for these changes was to make a metric specifically suitable for clinical application. Removing the requirement for an intact contralateral scan still required an intact limb surrogate, but allowed for expediting of the assessment process to clinically relevant time-scales (~15 minutes per case) and increased the clinical utility of the fracture severity metric. However, this work did not calculate fracture energy directly, instead focusing on more abstruse predictive metrics. These expedited methods were based upon identification and normalization of the quantity of de novo fracture area in relation to bone density. Fragment dispersion and articular comminution were also incorporated in the analysis.

The focus of the present work was to expand these prior efforts in objectively evaluating fracture severity by calculating fracture energy in any articular joint. In contrast to the prior objective severity assessments, this method for calculating fracture energy aimed to maintain the speed of the expedited metric, by minimizing manual intervention, and to expand the clinical utility of the method to allow for use on any articular joint, by not requiring the use of an intact contralateral or intact surrogate.

1.6 Rationale for Expanded Severity Metric:

Previous work successfully demonstrated that objective fracture severity metrics are an excellent tool for assessing injury severity in the plafond. Specifically, the fracture energy calculation showed strong predictive capabilities for the development of PTOA at a time of two years following the surgical treatment. These metrics have the potential to be integrated into the clinical setting to help guide a surgeon's approach to an injury. As previously discussed, there has also been promising work on development of an objective severity metric that can be obtained on clinically relevant time scales. This expedited assessment methodology, however, did not directly evaluate the fracture energy, but instead relied on more abstract indicators of injury severity.

The largest limitations for these extant fracture energy metrics has been the requirement either of a CT of the intact contralateral bone for the fracture energy calculation or the assumption of an anthropometrically scaled "normal" tibia and their singular study of the same 20 tibial plafond cases. These relatively restrictive requirements limited the clinical utility of the method to a single joint and necessitated the attaining of an intact contralateral CT scan or of additional anthropometric data. The fracture energy computation proposed in this paper aims to solve these problems and thereby increase the clinical and practical utility of an objective fracture energy metric. The methods developed are detailed, as is the application of these methods to assess fracture severity in a variety of joints.

CHAPTER 2: METHODS

The motivation for creating a new means for obtaining an objective fracture severity metric stems from the need to improve upon current fracture classification schemes used clinically. Where prior methods have yet to be used for joints other than the ankle, the methods developed and described herein are intended to be more broadly applicable. The methods build upon the foundations of these previous methods by generating an accurate estimate of fracture energy based solely on CT scans of the fractured bone. No intact contralateral or surrogate representation of an intact limb is required. Through the use of an automated trained classification system designed for identifying bone surfaces as either native or de novo, fractured surface area can be directly determined in a 3d working environment. This advance facilitates the study of a larger number of cases and supports application of the severity metric in joints other than the tibial plafond.

The research performed in this study involved both clinical and computational components. Orthopaedic surgeons at the University of Iowa Hospitals and Clinics, the University of Indiana, and the University of Utah performed the clinical work in collaboration with the author. The computational components of the work were performed by the author or under his direct supervision, building upon previous research conducted in the Orthopaedic Biomechanics Laboratory at the University of Iowa.

2.1 Segmentation and Model Creation:

The fracture energy calculation is based upon 3d surface models of fractured bone identified and segmented from CT scan data. Segmentations were first performed using purpose-written MATLAB code originally developed by Thaddeus Thomas Ph.D., Andrew Kern M.S., and Donald D. Anderson Ph.D. to automatically identify and separate fracture fragments with minimal user intervention. From these segmentations, 3d models were produced and analyzed to identify new surfaces of the bone liberated in the fracturing process. This process relied heavily upon a surface classification algorithm trained to recognize different surfaces based upon geometric and image intensity features. However, the segmentation task itself remains the most labor-intensive component of objective fracture severity analysis.

Differentiation of human bone from surrounding soft tissues within CT images is a challenging task. In CT imaging, normal cortical bone is easily discerned from surrounding muscle, fascia, and other soft tissues. However, cancellous bone is relatively less dense as a consequence of its porous trabecular nature. This can lead to cancellous bone having similar attenuation values to its surrounding soft tissues. When cortical bone is intact, cancellous bone is easily identified, as it is completely bounded by the denser cortical shell. However, when the cortical shell is fractured it can become difficult to discriminate between the soft tissue and the cancellous bone due to similar attenuation values. This is the primary need for user intervention and the limiting factor in decreasing the segmentation time.

Once bone/bone fragments were segmented from the CT scans in the purpose-written MATLAB code, the scans were loaded as NIFTI files into ITK-SNAP. This step was performed to correct any minor errors and inconsistencies remaining in the segmentation as a result of the inherent difficulties described above in performing an automated segmentation. After these corrections were completed, ITK-SNAP was utilized to export all fragments as individual STL models, the 3d model format used later in the de novo fractured bone area measurement. The STL models were then imported into Geomagic for a semi-automated smoothing and decimation routine to attain a more accurate representation of the bony surface and prepare it for subsequent fracture severity computation. Each properly prepared STL surface file of a fracture fragment was then saved to be imported into the MATLAB bone surface classification algorithm (Figure 2-1).

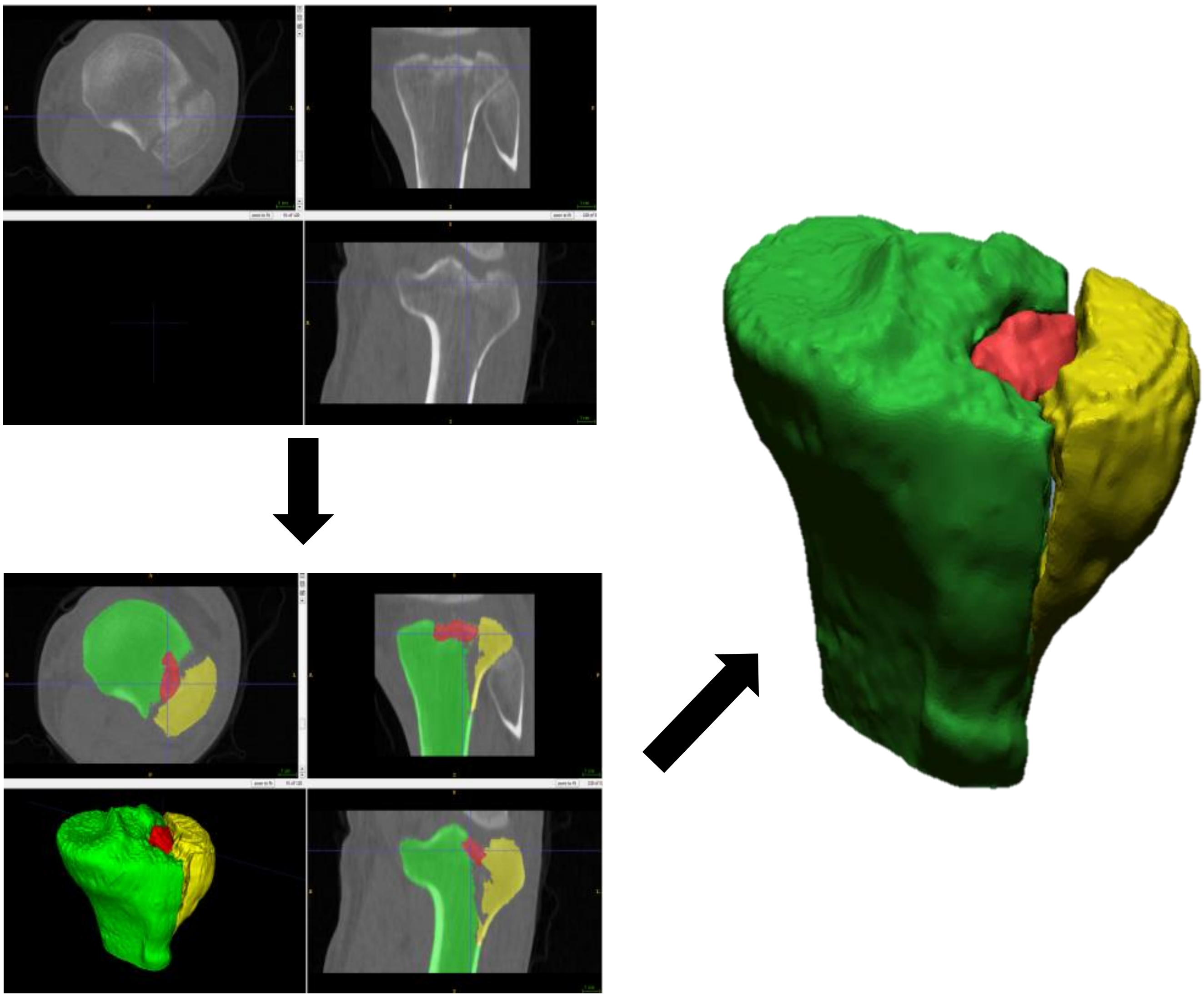


Figure 1-1. Workflow for fragment model creation from CT scan to segmented model to smoothed and decimated surface.

2.2 Classification:

The classification of separate bone surfaces was performed to distinguish intact and fractured bone for use in the severity analysis. Initial sets of fractured bone fragments in which the intact and fractured surfaces had been painstakingly manually identified were utilized to train a classifier leveraging the MATLAB function ‘predict’. This function offers a number of different machine learning classification strategies and options. For present purposes, a Naïve Bayesian Classifier was trained. This is a simple technique for discriminating between classes. It assumes that each feature used to differentiate between classes is independently predictive of the probability it will have a specific classification. Specifically, this is implemented through the following formulation to minimize the expected classification cost:

$$\hat{y} = \arg\min \sum_{k=1}^{K} \hat{P}(k|x)C(y|k)$$

Where $\hat{y}$ is the predicted classification, K is the number of classes, $\hat{P}$ is the posterior probability of class k for observation x, and $C(y|k)$ is the cost of classifying an observation as y when its true class is k.[43-45]

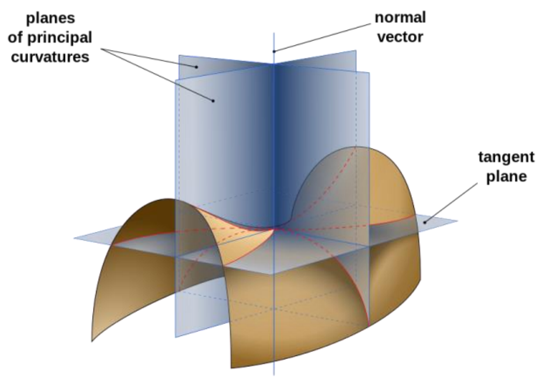
There were eight features selected for use in the naïve Bayesian classifier chosen based on their ability to best delineate fractured surface area. There were 6 image intensity based features and 2 geometrically based features. The image intensity based features included the CT Hounsfield units, the image sheetness, and variations of the two at different depths. The image sheetness is a second derivative image capable of detecting both direction and magnitude of edges shown in Figure 2-2 as contrasted

against its original CT data. Obtaining the CT Hounsfield unit values from the STL models was accomplished using the mean of the normal vectors on each face attached at a vertex for all vertices. The normals of the STL models generated in the segmentation process were projected into the CT image at 5 depths ranging from 0mm to 2mm at 0.5mm intervals from the vertex as shown in figure 2-2. The Hounsfield Unit intensities at the nearest voxels were interpolated for use in classification. The mean, standard deviation, and difference in HU between the 0mm and 2mm depths were computed on both the CT and sheetness images and comprised the 6 image intensity based classification features.

The two geometrically based classification features were obtained from STL models' vertices without relation to the image based intensity information. This is analogous to how the prior fracture energy metric had identified fractured regions with the exception of now being computed in three dimensional space. The minimum, maximum, and gaussian surface curvatures, exemplified in Figure 2-3, at each vertex were computed for use in training the classifier [46, 47]. The maximum and gaussian curvatures were directly included in the training of the classifier while the minimum curvature was indirectly included as it was required for computation of the gaussian curvature. These curvatures were included to help the classifier better detect fractured regions as intact bone regions tend to have lower curvature and fractured bone tend to have higher curvature.

0mm	0.5mm	1.0mm	1.5mm	2.0mm
700HU	650HU	625HU	400HU	400HU

Figure 2-2: Comparison of CT (top) and Sheetness (bottom) images at 5 depths between 0 and 2mmalong the vertex normal as shown by the arrow and lines on each graph.



Gaussian curvature is computed using the normal vector to define normal planes to the surface then identifying the intersection of the surface with the planes and multiplying the minimum and maximum curvature at that location.

Figure 2-3: Gaussian Curvature Definition[1].

These features were then passed to the classifier which, based on the 3 training data cases, computed the probability each vertex had of being fractured or intact. If the probability of being fractured was greater than 0.5, then the vertex would be classified as fractured. A flowchart demonstrating the classifier logic is shown in Figure 2-4. The generation of fractured vertex probability is based upon the equation described earlier in this chapter. Each vertex feature is assumed to be independent from the other features and therefore, each contributes independently to the probability the surface will be classified as fractured. This probability is based upon the likelihood the vertex would be classified as fractured with a given value of a feature in the set of training data. After predictions were made, data was displayed in the 3d interface. In this interface, faces were classified as fractured if they contained 2 or more vertices identified as being in the fractured region. Manual editing of the classification was then enabled on each fracture fragment.

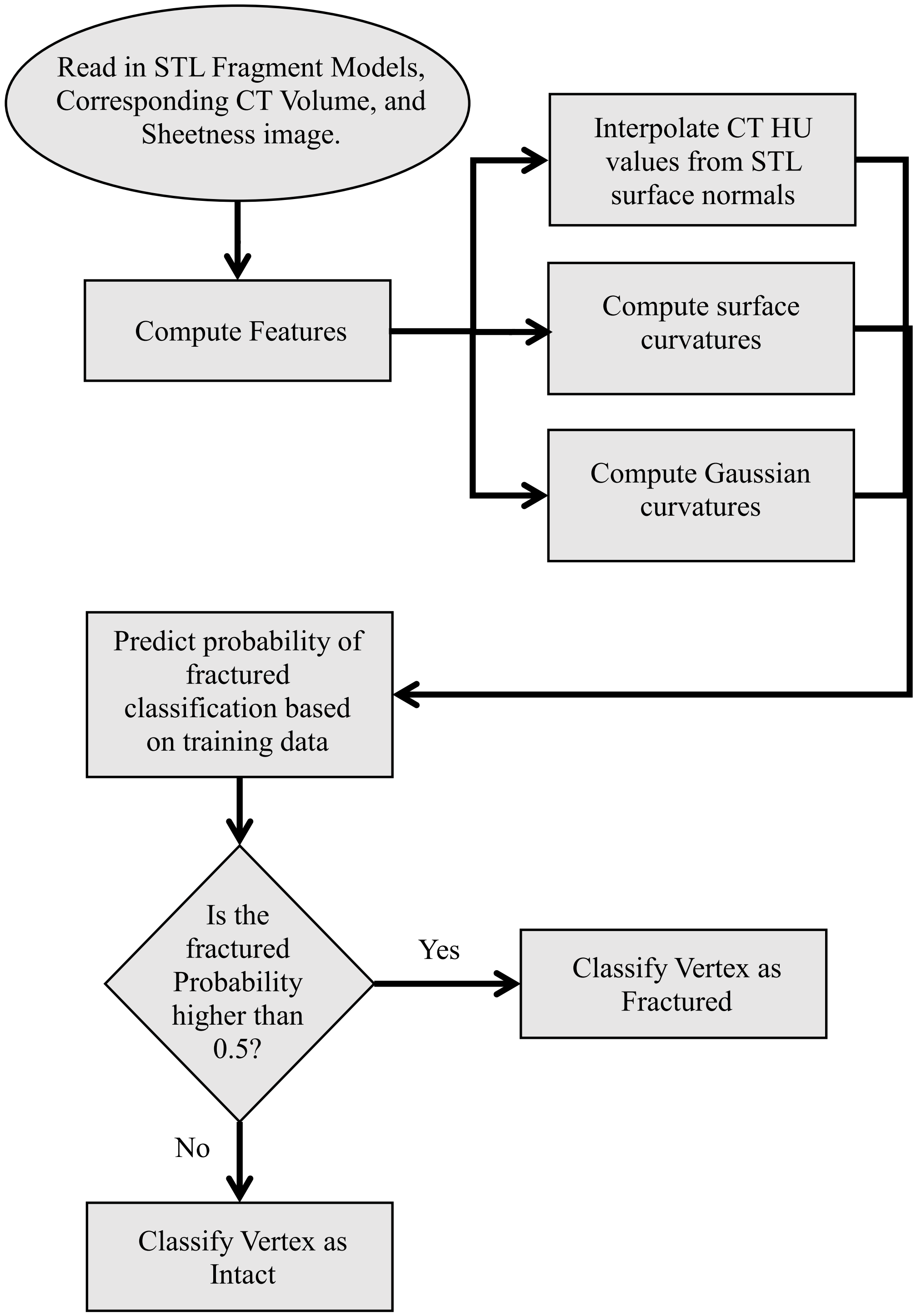


Figure 2-4: Logic of Naïve Bayesian Classifier applied to predict de novo fractured bone area.

After the probability of each vertex being classified as fractured or intact is computed, identification of the fractured surface area is not complete. If only the classifications based upon the Naïve Bayesian Classifier were used, the surface would be divided into heterogeneous regions with improperly classified vertices scattered throughout. In order to achieve homogenous fractured and intact regions, a graph cut algorithm was used to separate the regions on each fragment (as shown in Figure 2-5). A minimum-cut/maximum-flow (min-cut/max-flow) algorithm was implemented to create the cut. The minimum cut is defined as the cut that has the lowest edge cost. Edge costs, used in the building of this tree, are defined from the predicted classification probabilities and the surface curvatures (normalized between 0 and 1).

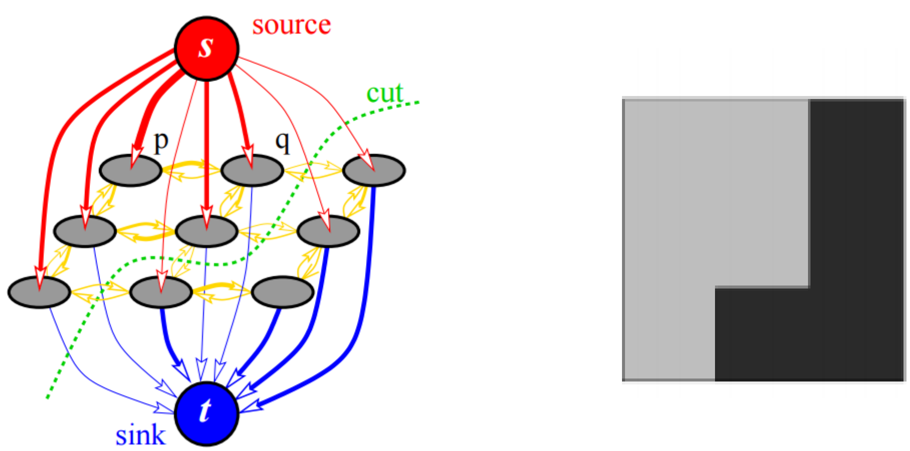


Figure 2-5: Left - An example of a graph cut separating two regions is shown here by the green dotted line. Edge costs are reflected by their line thickness. Right – regions as separated by the cut shown[48].

After the graph cut was used to nominally define the intact and fractured regions, any spurious region classifications were corrected through a 3d user interface. The STL model of each individual fracture fragment was isolated and viewed independently of the other fragments to allow for errors in the classification to be corrected. An example of a small typical error in the classification can be seen in Figure 2-6 for illustrative purposes. Errors in the classification typically occur in the cortical bone in areas of relatively high curvature. The area circled shows such an error in the classification of the right-most fragment in the model. The fragment is selected (shown highlighted in red on top left and middle left) and viewed independently (middle) in order to correct the classification. All fragments were visually inspected to ensure that the classifier had correctly identified fractured and intact regions of bone. This process can be repeated as many times as necessary on each fracture fragment until the classifications are deemed to be correct.

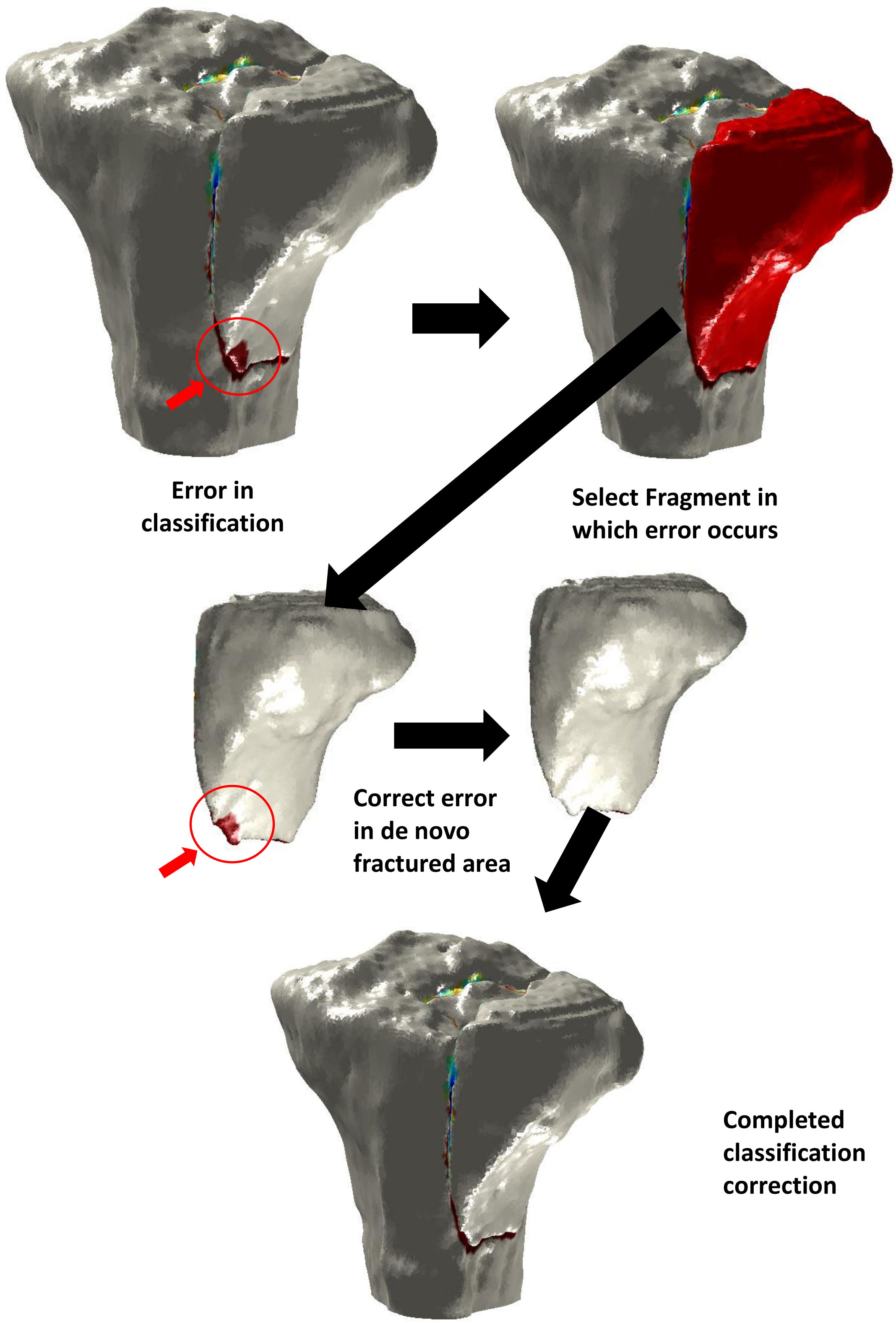


Figure 2-6: Classification Correction Work Flow

2.3 Severity Computation:

The fracture-liberated surfaces were then utilized to estimate the energy of the fracture. All faces of the bone fragment models with 2 or more vertices classified as fractured were included in the fracture area computation. The closest CT Hounsfield Unit (HU) intensity was then determined at the 3 vertices and averaged to obtain an approximation of the bone density at that area. The fracture energy was then determined using the following equation:

$$\boldsymbol{Energy}(\boldsymbol{J}) = \frac{1}{2} * [SA_{liberated}(m^2)] * \left[\left(\frac{HU}{10^{2.87}} \right)^{\left(\frac{1}{1.45}\right)} \left(\frac{g}{m^3} \right) \right] * \left[\left(\frac{12000}{1.98} \right) \left(\frac{J * m}{g} \right) \right]$$

Where: the first bracketed term, SA, is the surface area scaled by ½ in order to account for only the new surface area generated along the cut plane of the fracture and not both sides of the cut plane on each fracture fragment as is segmented; the second bracketed term represents the density based upon the CT Hounsfield Unit intensity, shown in the equation as HU as determined by Snyder et. al. in 1991;and the third term is the density dependent energy scaling factor empirically determined in prior work by Beardsley and implemented in this form by Thomas[3, 10, 41, 49, 50]. Figure 2-3 demonstrates the classification of surface area into intact and fractured bone. The colored region shows the de novo fracture liberated surface area with the densities shown. In essence, this provides an idea of where the energy was released from in the fractured bone as higher density bone is associated with higher fracture energy through the equation above. The density is calculated in the second portion of the equation from the CT Hounsfield Unit intensity in grams/meter^3.[3, 49]. This density is then scaled by an empirically derived energy release

rate for human bone. This energy release rate is the same across all cases analyzed and does not account for patient factors such as age or gender. This is a limitation of the study as it is known that bone will have different mechanical properties depending upon patient factors. However, in prior work it was established that these differences were relatively minor in the context of the articular fractures being studied.

Another limitation is that acquisition-specific CT-parameters were not accounted for in the calculations. There are numerous CT-parameters that might affect the results on a case to case basis. The first is the voxel size. Smaller voxels offer better resolution and therefore, the potential for more accurate discrimination of the fractured area. Larger voxels affording poorer resolution are then more prone to less accurately identified fractured area. This difference was accounted for in the data selection process. Only scans with all voxel dimensions less than 1mm were evaluated. Fortunately, modern CT acquisition protocols for articular fractures routinely deliver spatial resolutions in this range. Any error in the boundaries of the fractured area due to the voxel sizes is likely to be random and therefore averaged out. Another problem with large voxel sizes is partial volume effects. This occurs when the voxel is too large to capture the details smaller than the voxel size itself. For example, in this study, voxels along the fracture edge are likely to only be partially filled with fractured bone. Since the Hounsfield unit value of the voxel is the averaged intensity of the less dense water and the more dense bone, the fractured edge may appear less dense than reality. To account for this factor, the Hounsfield units were sampled 3 voxels in along the surface normal along the fracture boundary.

The other acquisition specific CT-parameter that has bearing on the fracture energy calculation is the convolution kernel used to reconstruct the image. Convolution kernels are designed with one of two primary purposes: to create an image to improve discrimination of bony edges or to improve ability to detect low contrast soft tissue structures. The images created from kernels used for bony edge detection are susceptible to pixel noise appearing grainy while soft tissue kernel images appear smooth and lack highly defined bony edges. To account for these differences, an anisotropic diffusion filter is applied during segmentation to enhance bony edges and smooth pixel noise for accurate model creation. As this filter changes the image HU intensity values and could affect outcomes, the original CT scan acquisitions are used after the segmentation step to be sampled in severity computation.

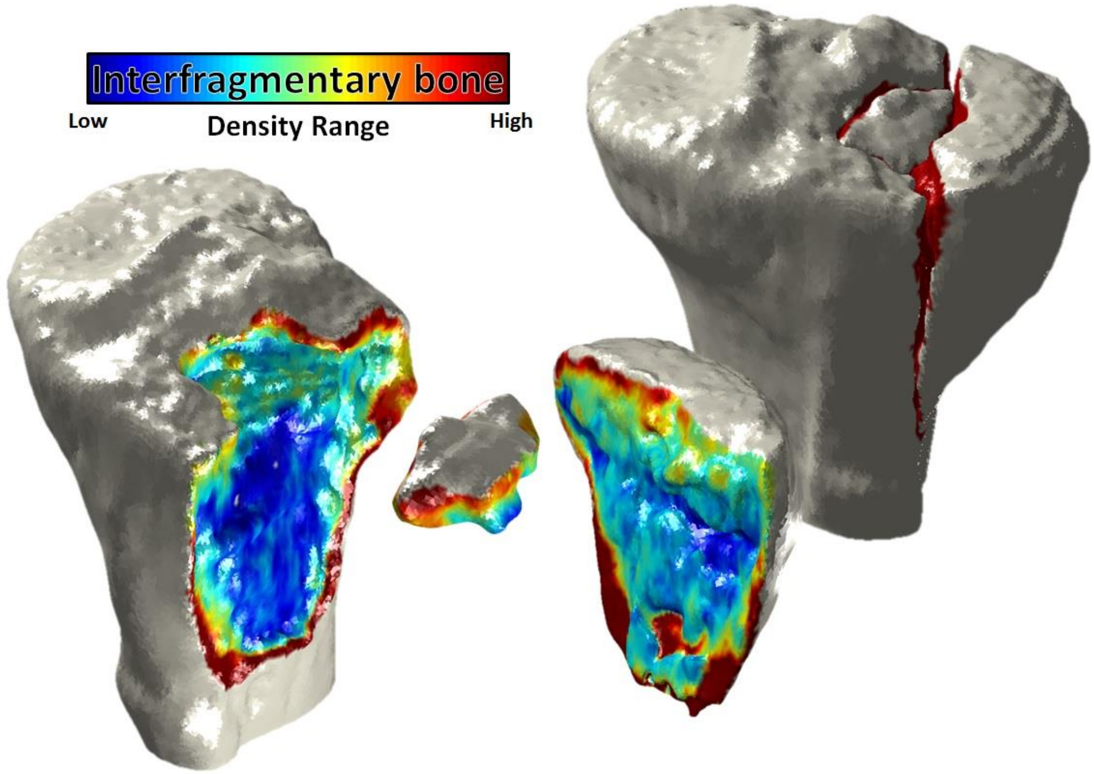


Figure 2-7. The fracture-liberated surface area and bone density values used to calculate fracture energy.

2.4 Clinical Data Gathering:

The initial 20 tibial plafond fracture cases that were the focus of prior development work had been obtained under an NIH-funded grant investigating PTOA. These prior cases, for which previously validated methods had been used to measure fracture energy, were used for validation of the present method. Additional fracture cases were provided under grants from the NIH and the Foundation for Orthopaedic Trauma, in collaboration with the University of Indiana and the University of Utah.

2.5 Plateau Rank Ordering:

In collaboration with the University of Indiana, a comparison of the computed fracture energies and surgeon assessment of fracture severity for 20 tibial plateau cases was performed. The 20 cases were selected by a fellowship-trained orthopaedic trauma surgeon to fully span the spectrum of fracture severity. The cases to be rank ordered by severity were taken from a larger series of 50 tibial plateau fractures by a fellowship-trained orthopaedic traumatologist. Fracture classifications ranged from OTA 41-B3 to 41-C3.[26] IRB approval was obtained from both institutions. Patients included in the study ranged in age from 18 to 70-years-old. There were 12 males and 8 females.

The purpose of this study was to determine the capability of an objective CT-based fracture energy metric to assess fracture severity by comparing it to the current gold standard; the subjective expert opinion of orthopaedic traumatologists. Assessment of expert opinion was done by rank ordering the cases.

The raters were given a PowerPoint with 20 slides corresponding to the 20 cases. Each slide contained an AP and lateral plain radiograph of the cases. The raters were asked to view the slides in the slide sorter view with occasional inspection of individual slides as needed. Figure 2-8 shows the PowerPoint format the surgeons were asked to use in ordering the cases. With the slide sorter view open, they were asked to order them based upon severity with the first slide being the least severe and the last slide being the least severe. They were asked to save the PowerPoints with their finalized ordering and

return them for use in the study.

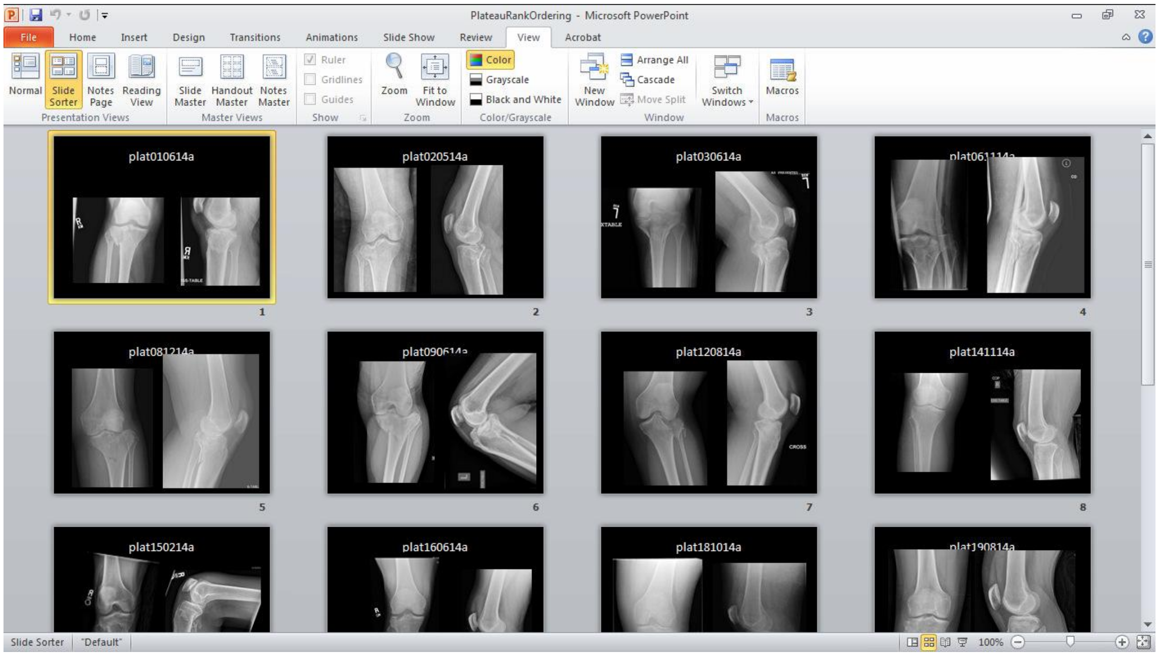


Figure 2-8: PowerPoint format used for ordering plateau fracture cases.

Similarly, the fracture energy for each case was determined and the cases were rank ordered from lowest to highest energy. This ordering was then compared with the ordering of the expert raters. Concordance, a measure of agreement between rankings, between the raters and the fracture energy was then computed.

<u>2.6 Concordance:</u>

Concordance is a statistical method with which the probability of two cases having the same ordinal ranking by two different raters or methods can be measured. Concordance is determined by taking the number of concordant pairs of ratings divided by the total number of possible pairings. A pair of ratings is deemed concordant if cases with higher rankings by one rater or metric are also ranked higher by a second. A perfectly random assignment of rankings between two reviewers would then produce a

concordance of 0.5, as any case pairing would have a 50% chance of being concordant. This method was utilized in all studies where comparisons of ranking and/or classification were evaluated.

Ranking Position	Rater 1:	Rater 2:
1	A	A
2	B	B
3	C	D
4	D	E
5	E	C

Concordance is found by taking all possible pairs of ratings that occur at the same position between raters and calculating the number of concordant pairs divided by the total number of pairs. If there is a tie between ratings in a pair (as there often is when rating using a finite classification system), then it is counted as having half of the value of a truly concordant pair. Simply put, if the sign (i.e. >,<) of the pairs are the same, then the pairs are concordant.

Position Ranking Comparison	Rater 1 Ranking	Rater 2 Ranking	Concordant pair (1 for concordant, 0.5 for ties and 0 for non-concordant)	Total pairs
Position 1 vs 2	**A < B**	**A < B**	**1**	1
Position 1 vs 3	**A < C**	**A < D**	**1**	2
Position 1 vs 4	**A < D**	**A < E**	**1**	3
Position 1 vs 5	**A < E**	**A < C**	**1**	4
Position 2 vs 3	**B < C**	**B < D**	**1**	5
Position 2 vs 4	**B < D**	**B < E**	**1**	6
Position 2 vs 5	**B < E**	**B < C**	**1**	7
Position 3 vs 4	**C < D**	**D < E**	**1**	8
Position 3 vs 5	**C < E**	**D > C**	**0**	9
Position 4 vs 5	**D < E**	**E > C**	**0**	10
		Total	**8**	10
		Concordance	**80%**	

The 80% concordance found here corresponds to a 80% chance that two cases will have the same ranking by rater 1 and rater 2.

Figure 2-9: Concordance calculation example

2.7 Schatzker Classification:

Performed in cooperation with the University of Utah, Schatzker classification of tibial plateau fracture was compared with fracture energy. A series of 40 patients with tibial plateau fractures were consented for the study. Standard of care pre-operative CT scans were obtained and used to clinically assess severity by classifying cases according to the Schatzker classification. The series contained a variety of plateau injuries ranging from Schatzker classification I to VI fractures as judged by expert surgeons at time of injury. The pre-operative CT scans were also segmented and used in determination of fracture energy. As fractures with higher Schatzker classifications are generally considered to be more severe, the classifications were used to rank the severity of the fractures. Accordingly, the fracture energy measure was also used to rank order the 40 cases. Concordance between the Schatzker classification ranking and fracture severity ranking was then used to characterize agreement in their assessments.

2.8 Calcaneal Fracture Energy:

IRB approval was obtained for eighteen patients with nineteen intra-articular calcaneal fractures seen at the University of Iowa Hospitals and Clinics. The patients were selected from a series of 120 cases presently being followed. Pre-operative CT scans were obtained for all patients in accordance with the standard of clinical care to assess severity. Clinically, the Sanders classification was evaluated by a fellowship-trained orthopaedic traumatologist for each fracture, utilizing the pre-operative CT scans. Four expert surgeons also evaluated the post-reduction articular step-off to consider as a potential confounder.

The pre-operative CT scans were segmented and processed as described in chapter 2.1 for use in the in the fracture energy metric. Both fracture energy and Sanders classification (described in chapter 1.4.1) were used to assess initial fracture severity. The fracture energy and Sanders classification were then evaluated against post-operative outcomes. The Kellgren Lawrence (KL) grading system, developed as a radiographic indicator of arthritis development, was used to evaluate patient outcomes at their last followup [51]. The KL grading system categorizes radiographically perceptible changes in OA severity into 5 grades. A KL grade 0 indicates a radiographically normal joint with no visible arthritis and a grade 4 indicates severe radiographically detectable development of arthritis. Grade 2 has been considered to be the threshold for PTOA appearance. This grading scale was then used to judge the predictive abilities of both the Sanders classification and fracture energy metric.

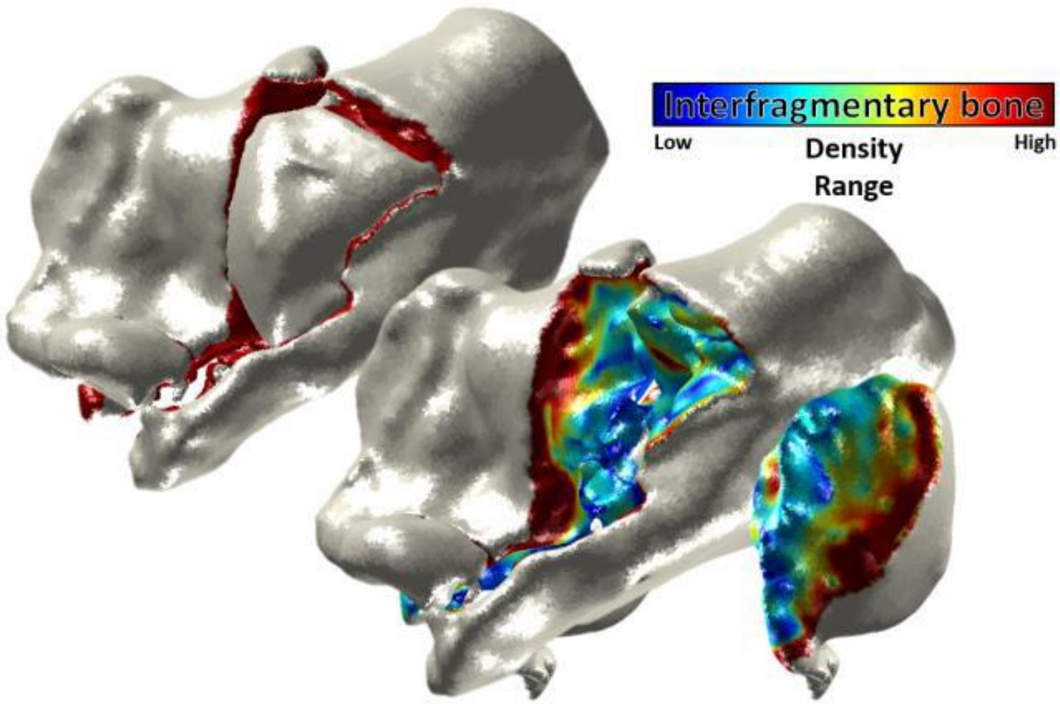


Figure 2-10. 3d model of a Sanders class III intra-articular calcaneal fracture. Left: inter-fragmentary surface area (red). Right: inter-fragmentary bone with bone density range.

2.9 Fracture Energy Comparison:

A combined effort between the University of Iowa, University of Indiana, and University of Utah hospitals has resulted in over 109 total fractures of the tibial plafond (31 cases), plateau (61 cases), and the calcaneus (17 cases) for study. The same, versatile fracture severity assessment methodology was shown to be capable of handling these 3 diverse injury types. This allowed an unprecedented direct objective comparison of injury severity between the three different types of fractures. The range of fracture energies in this study is expected to be similar across injuries with similar mechanisms.

CHAPTER 3: RESULTS

The fracture energy assessment methodology was applied to analyze 3 different joints in 2 different fractured bones; energy of fractures was determined in the tibia for the tibiofemoral (plateau) and tibiotalar (plafond) joints and in the calcaneus for the talo-calcaneal (subtalar) joint. Pre-operative CT scans were obtained for 61 plateau, 31 plafond, and 19 subtalar joint fractures from 3 institutions.

3.1 Fracture Energy Assessment

The fracture energy assessment used in this thesis was computed on all 111 cases studied. For these cases, the average time to segment and prepare models for the classifier as described in chapter 2.1 varied but took on the order of 30-45 minutes per case. The classification of de novo fractured area, detailed in chapter 2.2, for the cases was much faster; the classification took between 1 and 15 minutes depending upon the amount of classification correction performed. The calculation of fracture energy occurred after the classification and never required more than 1 minute to complete.

3.2 Fracture Energy Validation

The fracture energies computed using the new assessment methodology were compared against those computed using the prior method for validation purposes. The twenty tibial plafond cases previously analyzed were evaluated using the new methodology. A comparison between the results are shown in figure 3-1. There was a strong agreement between the previous fracture energy measure and the present fracture energy measure with an R^2 correlation of 0.9434. On average, there was a bias that the prior methodology measured around 1.5J higher than the present method; based upon

these cases, the data suggest that 95% of measurements with the new methodology will be within 3-5J of those made using the old method.

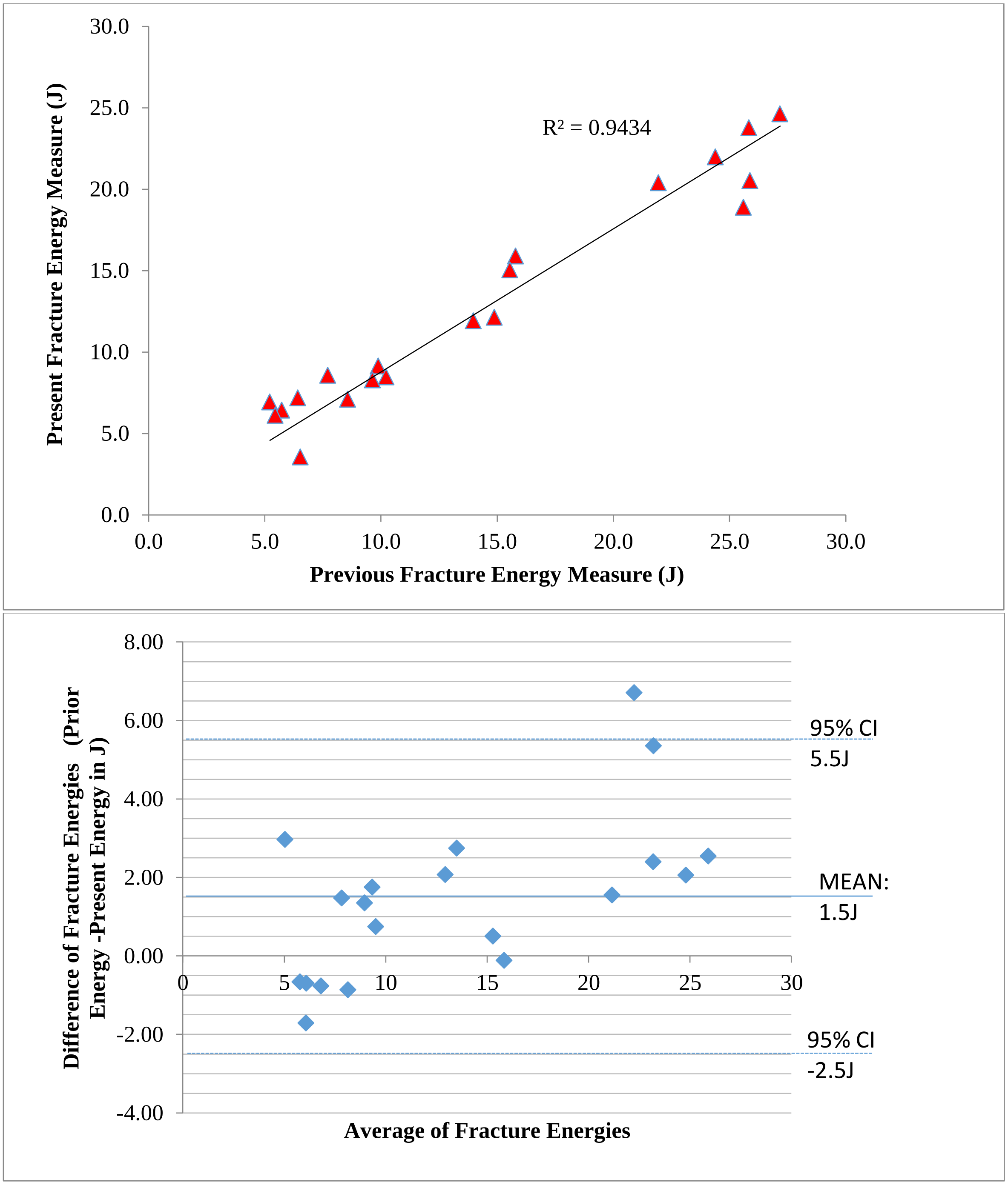


Figure 3-1: A comparison between the previously established fracture energy methodology and the present fracture energy method. Top: Graph of prior vs present energy methodologies. Bottom: Bland-Altman plot of prior vs present energy methodologies.

3.3 Plateau Rank Ordering:

The fracture energies computed in twenty tibial plateau fracture cases selected to span the injury severity spectrum ranged from 5.1 to 23.6 Joules (J). A high level of agreement was found between the six experienced orthopaedic trauma surgeons who completed the severity ranking. Concordances between the surgeons ranged from 82.1% to 92.6%, with a mean of 87.4%. The concordance between the surgeons and the fracture energy ranking of severity were slightly less high, ranging from 70.5% to 78.4%, with a mean of 74.7%.

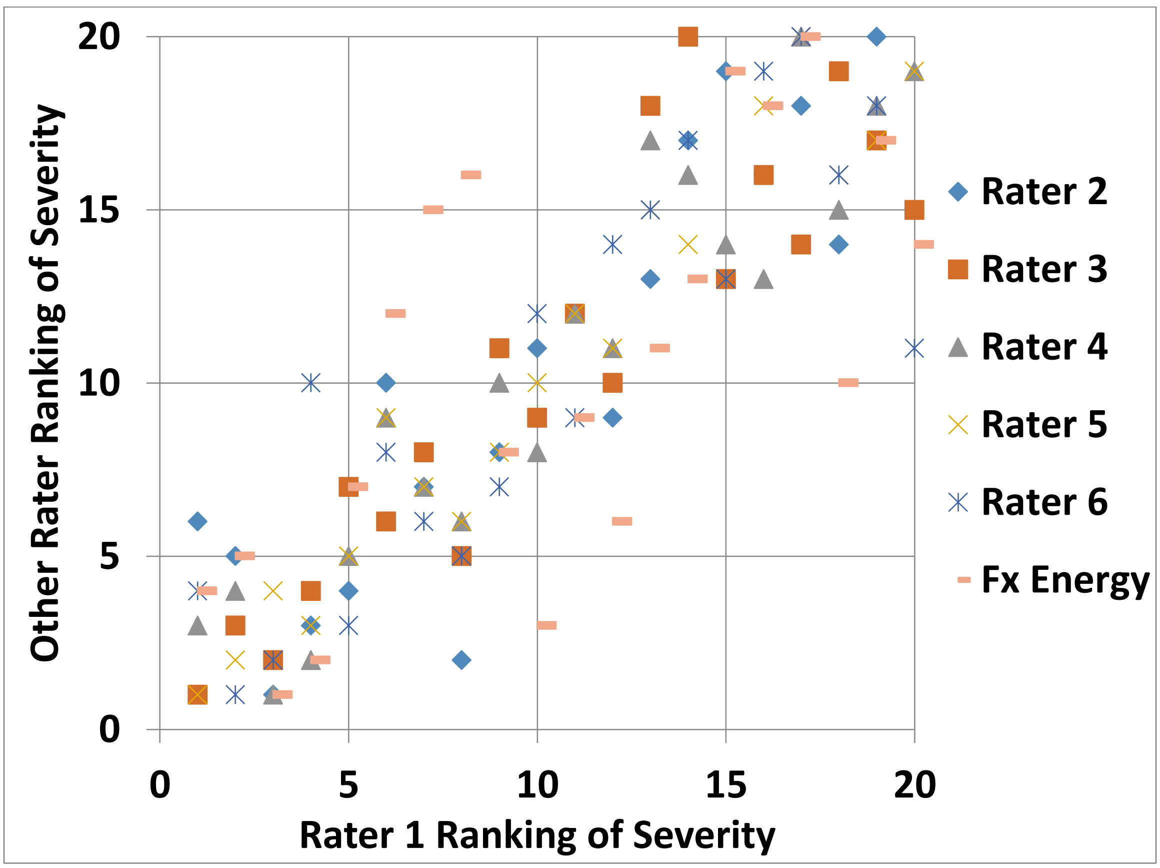


Figure 3-2: Rater 1 ranking of severity vs each individual ranking of the other raters.

Table 3-1: Concordance between six expert orthopaedic traumatologists and fracture energy

Rater	**B**	**C**	**D**	**E**	**F**	**Fracture Energy**
A	84.2%	87.4%	88.9%	92.6%	83.7%	**75.8%**
B		82.1%	86.8%	85.3%	84.7%	**76.8%**
C			86.8%	85.3%	81.6%	**70.5%**
D				92.1%	83.2%	**78.4%**
E					87.9%	**75.8%**
F						**71.1%**

3.4 Schatzker Classification:

The average fracture energy increased monotonically with increasing Schatzker classification. This indicates general agreement between the Schatzker classification and the energy involved in producing the fracture. Despite this general trend of agreement, the energies showed a significant degree of variance in some classes. Schatzker class II fractures, for example, had overlapping energy fractures with all other classes ranging from 3.2J to 17.7J fractures. This large degree of variance could easily explain outliers in previous studies that have utilized the Schatzker classification system as a surrogate measure of initial fracture severity.

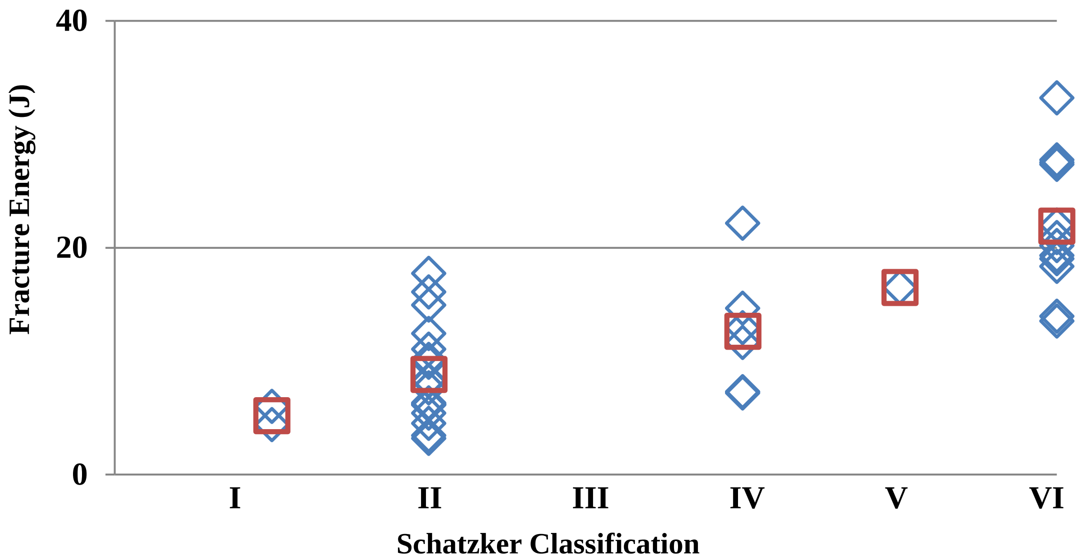


Figure 3-3: Schatzker Classification vs Fracture Energy with averages by classification (indicated by red boxes).

Table 3-2: Comparison of fracture energy and Schatzker Classification

Schatzker Class	Number of cases	Mean	Minimum	Maximum	Standard Deviation
I	2	5.2	4.4	6.0	0.8
II	19	8.8	3.2	17.7	7.3
III	0	N/A	N/A	N/A	N/A
IV	6	12.6	7.2	22.2	7.5
V	1	16.5	16.5	16.5	0.0
VI	12	21.9	13.5	33.2	9.8

3.5 Calcaneal Fractures:

There were 19 calcaneal fracture cases analyzed for severity. The fractures ranged in their nature from Sanders classification II to IV. The energy of the fractures ranged from 12.3J to 24.5J, with an average energy of 18.0±2.9J. Eleven cases were evaluated for PTOA development between 20 and 74 months post-operatively. A concordance of 75% was observed between the Sanders classification and the fracture energy measurements. There were more complex relationships observed between the KL grades, articular step-off, classification, and outcomes. Figure 3-4 demonstrates some of these relationships, with cases segregated based upon articular reduction quality. Figure 3-5 shows the relationship between fracture energy and Sanders classification, and figure 3-6 shows the relationship between Sanders classification and the KL-grade.

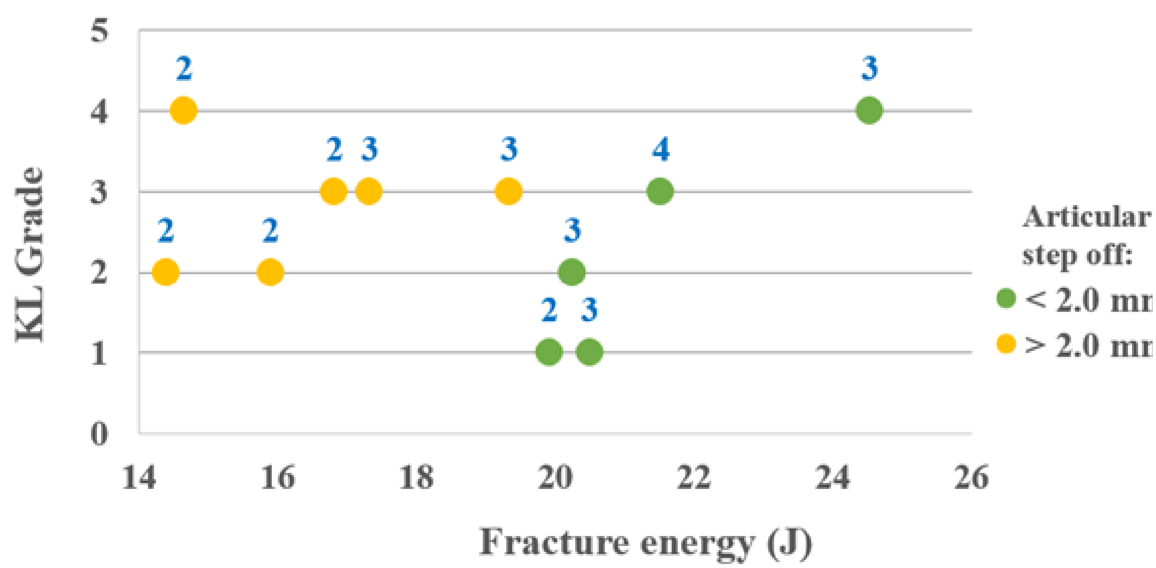


Figure 3-4: KL Grade vs Fracture Energy. Number above data points indicates Sanders classification.

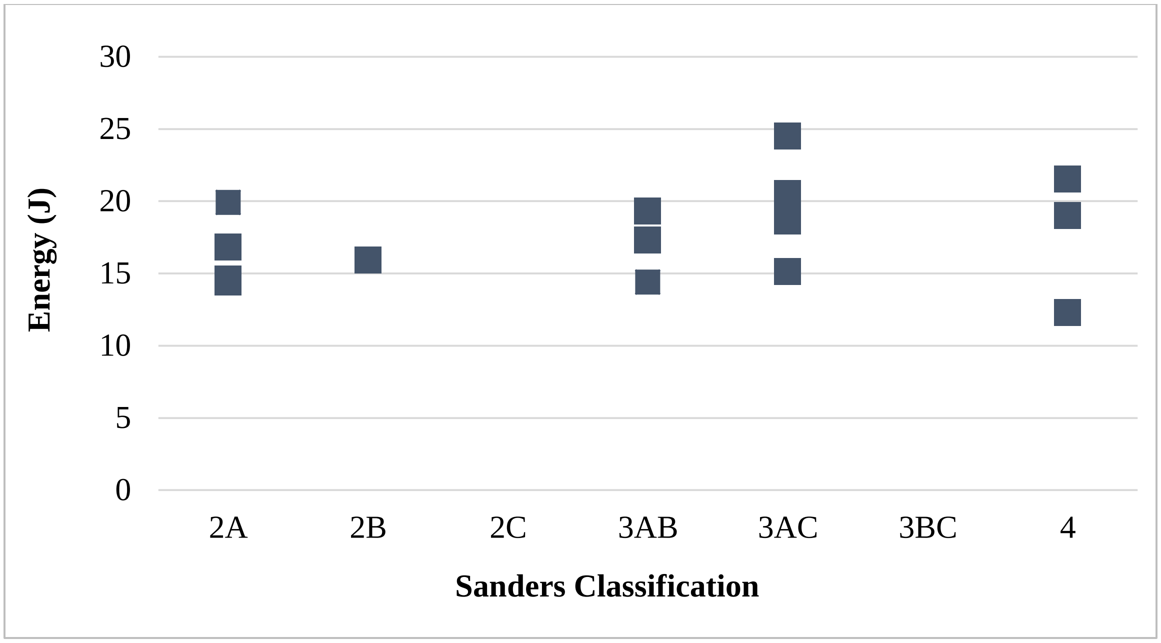


Figure 3-5: Fracture energy vs. Sanders classification subtypes.

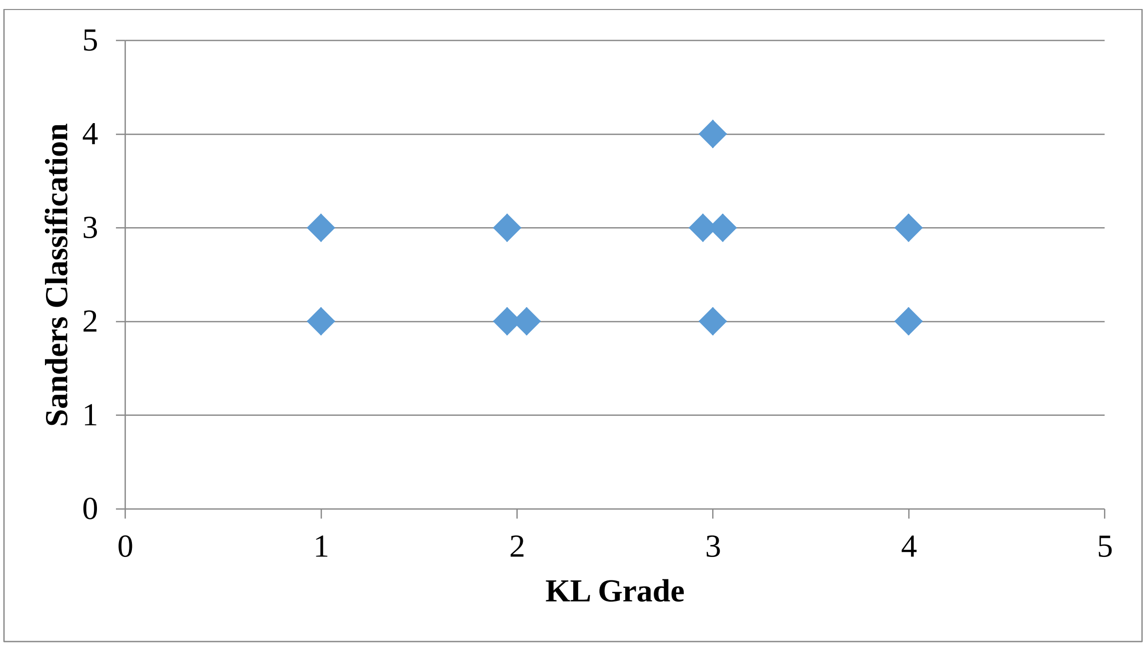


Figure 3-6: Sanders classification vs. KL Grade.

3.6 Comparison:

There were 31 plafond, 61 plateau, and 17 calcaneal fracture cases available for comparison in this study. The range of energies in the tibial plateau fractures was 3.2J to 33.2J with a mean of 13.1J and a standard deviation of 6.8J. The range of fracture energies in the plafond was 3.6J to 26.7J with a mean of 12.9J and a standard deviation of 6.4J. The non-selected series of calcaneal fractures ranged in fracture energy from 12.3J to 24.5J with a mean of 18.1J and a standard deviation of 2.9J. The relative distributions of fracture energies within the plafond and plateau cases were similar. The calcaneal fractures had a narrower range towards the higher end of the energy spectrum for the selected series that were studied.

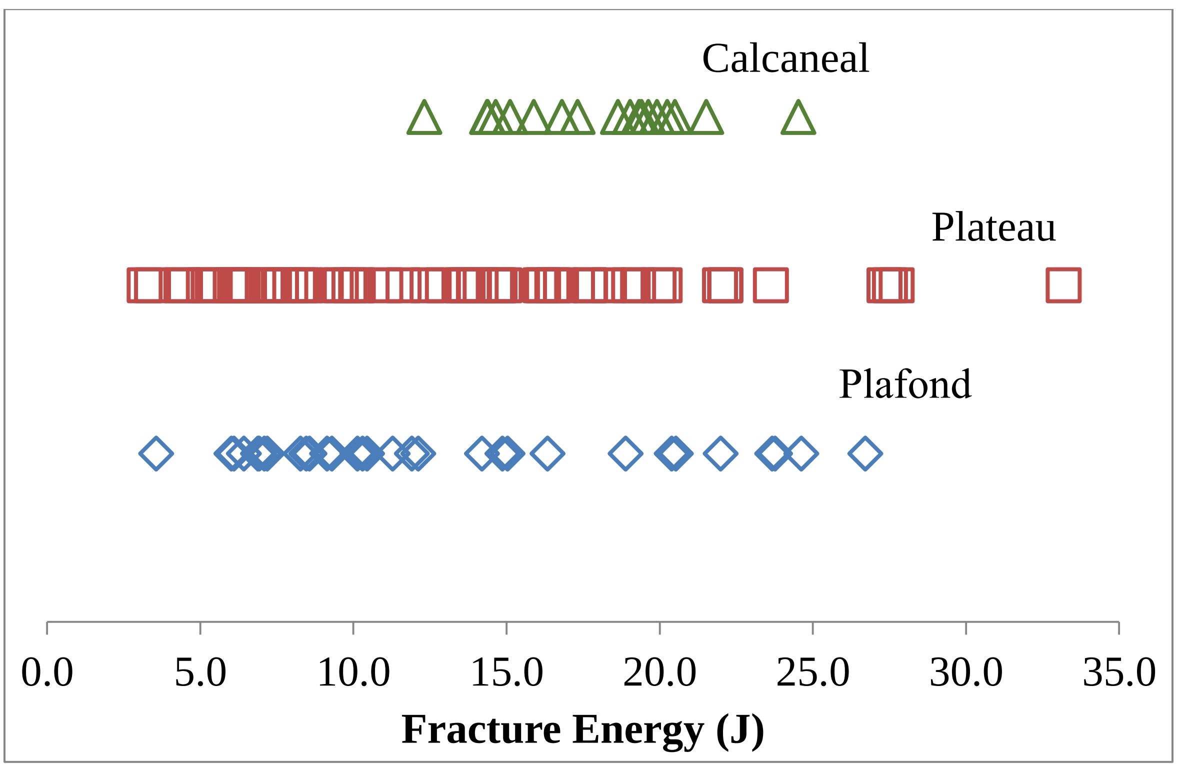


Figure 3-7. Plafond, plateau, and calcaneal fracture energy distributions

CHAPTER 4: Discussion

The primary purpose of the work reported in this thesis was to improve and expand upon existing objective fracture severity assessment techniques. The improvements allowed for the study of a large series of articular fracture cases, which made it possible to evaluate existing clinical injury severity assessment methods. Clinical severity assessments, while having practical utility, have been limited by their inability to scientifically capture characteristics predictive of long term patient outcomes. Previous metrics have identified and implemented objective CT-based techniques that more accurately identify intrinsic factors leading to poor patient outcomes.

Specifically, this study focused on a CT-based technique for objectively quantifying the amount of energy required to produce a fracture in a given bone. This intrinsic factor associated with intra-articular fractures (i.e., fracture energy) is of particular interest as these fractures often have poor outcomes and are typically the result of high energy injury mechanisms. Therefore, it was hypothesized that higher energy fractures would have poorer outcomes. The potential for future clinical application of this hypothesis, allowing for quantitative and objective prediction of patient outcomes, is considerable.

Exploration of potential locations where such a measurements might be most useful is the focus of this discussion. Determining the veracity of new energy metrics' utility in these locations is difficult as there is a paucity of information regarding what components of injury severity are most important. Therefore, when lacking long term

patient follow-up data, the present gold standards for predicting patient outcomes, clinician assessment and clinical severity classification metrics were utilized.

4.1 Fracture Energy Assessment:

The stated goals of the fracture energy assessment were to create a simple, robust, and versatile method for determining the energy involved in a fracture capable of being used in any articular joint. A secondary goal of the work was for the method to operate on a clinically relevant time scale. The simplicity of the method is such that any person able to identify fractures on a CT scan can perform the task. A 3d user interface guides classification of de novo fractured bone area and requires minimal correction in the form of visual inspection of each fractured fragment. Errors found in the classification, like the one shown in figure 2-2, tend to be obvious misclassifications in regions of high curvature. Errors such as these would be expected to be less frequent as the classifier gains access to a larger set of training data moving forward.

The method proved to be robust and versatile as it demonstrated efficacy in the knee, ankle, and subtalar joints. It was capable of working in every case on which it was applied. The secondary goal of operating on a clinically relevant time scale is a point of continuing effort. The method was close to, but ultimately fell short of being consistently under 1 hour. The most time-intensive component, accurate segmentation of fracture fragments, presently requires a significant degree of manual intervention. Fortunately, the time required for this component has the potential to be reduced significantly in future work. The primary objectives of this thesis to create a robust and versatile metric capable of being used in any articular joint were in direct opposition with the time to perform the metric. As all 111 cases in this work were evaluated in respect to clinical measures or

outcomes for research purposes, the segmentations were performed with great attention to detail in fracture fragment identification. Future work will determine the quality and time required for the segmentations to ensure acceptable accuracy in fracture energy evaluation.

4.1.1 Reproducibility

Although no formal study of CT segmentation reproducibility was performed, the same segmentation methods were used in prior work and shown to possess excellent reproducibility. A casual assessment of the reproducibility of segmentations was made using three training segmentation cases performed by two additional analysts. The maximum difference in the fracture energies computed for these cases between different segmentations was around 2 J. The author also noted maximum differences on the order of 2 J for several cases that required reprocessing for various reasons.

4.2 Plateau Rank Ordering:

The fracture energy metric had previously been validated in the tibiotalar joint against clinician assessment by rank ordering cases of varied severity. The next logical application for the energy metric was in the knee with plateau fractures; therefore, the fracture energy was used to rank cases and those rankings were then compared with the present gold standard of subjective expert surgeon rankings, as was done to evaluate the energy metric in the tibial plafond. Inter-user agreement between the six orthopaedic trauma subspecialists was high at 85% concordance. While the level of agreement between the surgeon assessments between fracture severity ranking and energy was not as high at 74%, it was still significantly higher than chance concordance of 50 percent.

There were notable outliers to the trend of concordance between the surgeon assessment and the fracture energy metric. For example, a case ranked the 3rd (6.4 J) on a scale from least to most severe by the fracture energy metric was ranked 10th on average by the surgeons. Another outlier was a case rated the 16th most severe (16.8J) by the energy metric and, 5th on average by the surgeons. Figure 4-1 shows the radiographs rated by the surgeons and the models used in determining the fracture energy for these two cases.

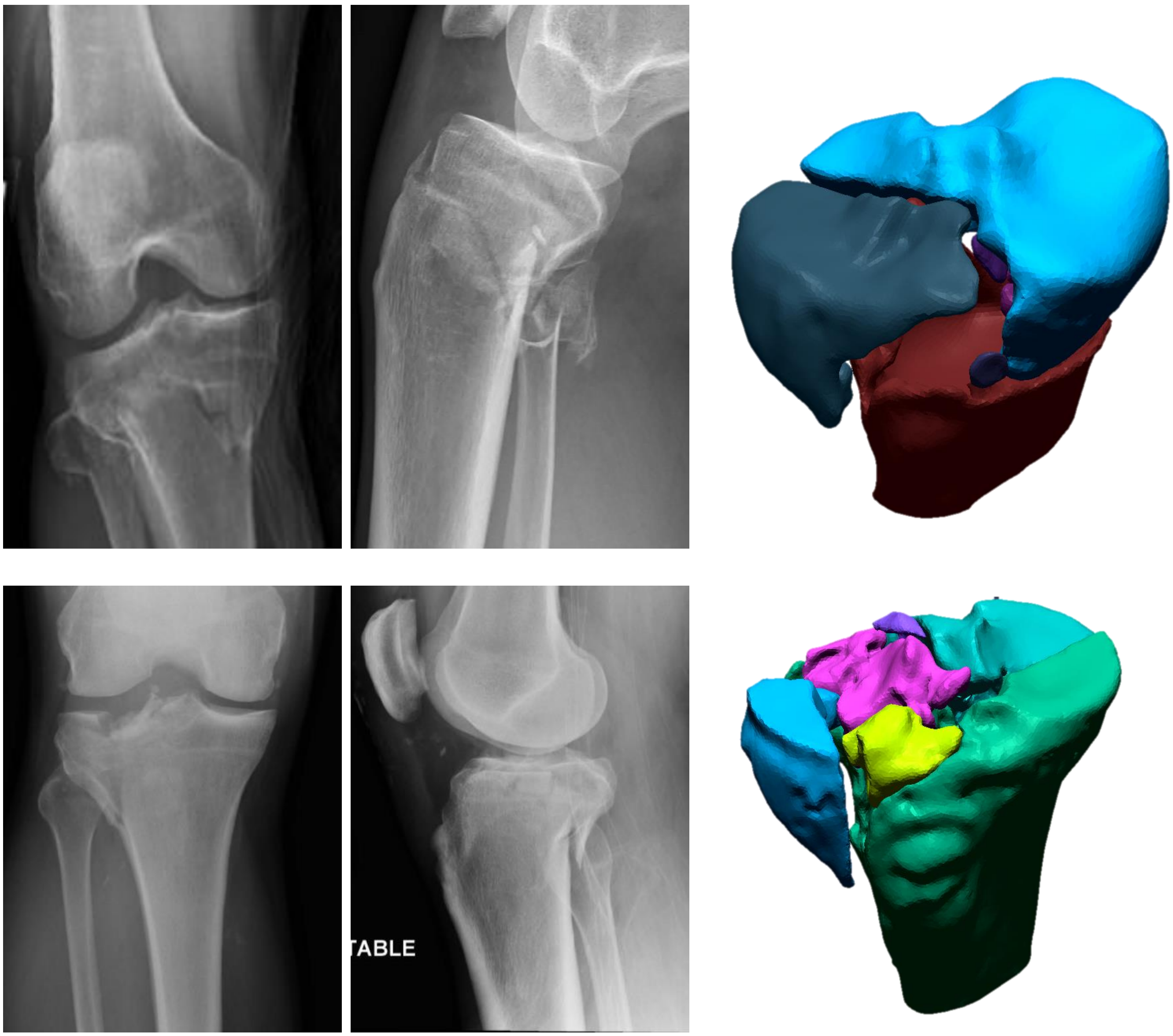


Figure 4-1: Examples of disparate clinician ranking and fracture energy. Top: Low energy 6.4J fracture with high surgeon severity ranking. Bottom: High energy 16.8J fracture with low surgeon severity ranking.

These two cases serve to illustrate important points about the fracture energy metric in comparison with clinician assessment. Patient-specific factors like osteopenia, fracture location, and comminution influence surgeon assessment of injuries but are not directly accounted for by the fracture energy metric. Of these factors, osteopenia is of interest as bone density contributes to the fracture energy measure because the energy absorbed in bone fracture scales directly with density. Lower energies are able to break osteopenic bone more readily due to its lower density. Presently, it is unclear how the fracture energy measure performs against outcomes in such cases, but given its divergence from surgeon ranking, it is possible the fracture energy may be more objectively predictive of outcomes than clinician assessment. However, other patient specific factors mentioned remain unaccounted for and are potential limitations of using only a fracture energy metric to assess severity.

Despite these limitations, fracture energy was shown to have acceptable agreement with expert opinion of injury severity of the entire spectrum of injury severity. Accordingly, the fracture energy metric was shown to have utility in joints other than the plafond. The importance of this result lies in the ability of the metric to quantify an underlying physical property of injuries and use it to objectively assess injury severity. This allows for analysis of a continuous spectrum of injury severity as opposed to a discretized clinical classification that can fail to appreciate subtle differences in fractures. Additionally, the objectivity of employing a calculable physical property prevents clinician bias present in subjective assessments, thereby improving reliability of results.

While the results of this study were promising, it is important to note that surgeon rank ordering does not provide a direct relation to patient outcomes. Therefore, further

investigation will be needed to determine if relationships exist between fracture energy and clinical outcomes. Prior studies in the plafond lend credence to the possibility that such relationships will be found. A 2010 study by Thomas et. al., found fracture energy to be a statistically significant prediction of PTOA at 2 years [10]. Overall, fracture energy in addition to clinician opinion shows strong potential to provide advantages in assessment of injury severity.

4.3 Plateau fracture energy and Schatzker Classification:

Following validation of fracture energy against clinician severity assessment in the tibial plateau, the metric was employed to evaluate the energy metric against the Schatzker classification of plateau fractures. The Schatzker system has well established clinical utility in guiding treatment and predicting outcomes, but its ability to stratify severity had never been assessed. It was designed to identify and group fractures based upon distinct pathomechanical and etiological factors. Additionally, the comparison to fracture energy is also notable due to the potential for further validation of fracture energy metric's predictive capability.

Fractures of the medial plateau (Schatzker IV and V) are typically considered to be more severe than lateral sided (Schatzker I and II) fractures. It might then be hypothesized that medial sided injuries have higher fracture energies, explaining in part the difference in outcomes. The results showed a general monotonically increasing relationship between mean fracture energy and Schatzker classification for the injuries. These results support the hypothesis that differences in outcomes between lateral and medial sided fractures may be explained in part by the initial energy involved with fracturing the joint.

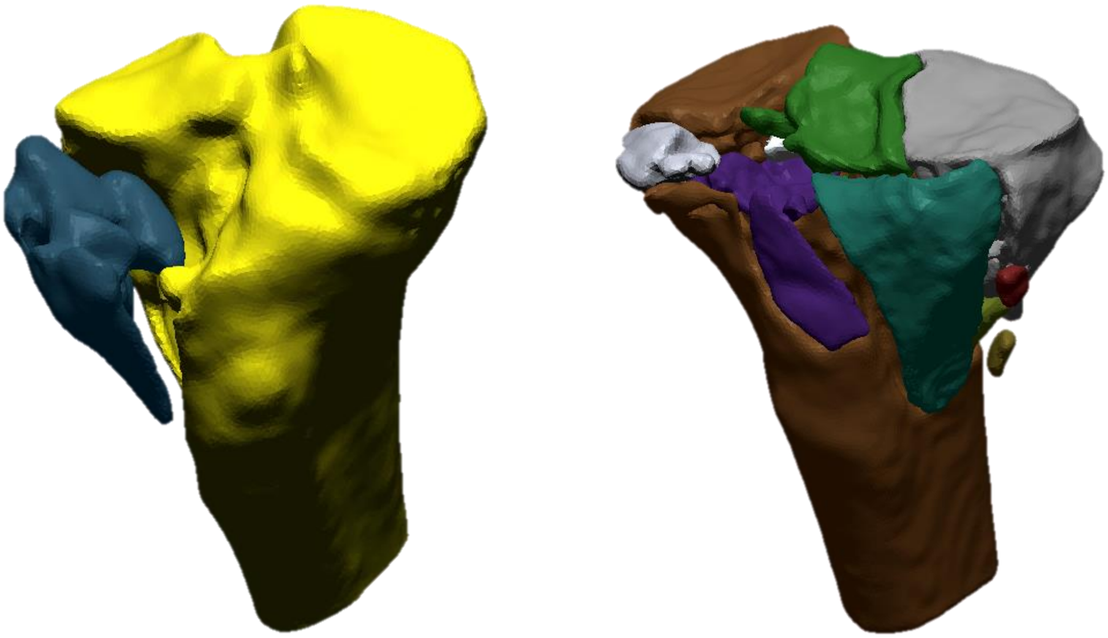


Figure 4-2: Low (left) and high (right) energy Schatzker Class II Fractures.

While the results show a monotonically increasing relationship between fracture energy and Schatzker classification, there was a large degree of overlap between all classes. These findings suggest promising clinical utility for the fracture energy metric in predicting outcomes. Lower energy higher classification fractures may have better outcomes while higher energy lower classification fractures may have worse. Further research into the interplay between Schatzker classification, fracture energy, and patient outcomes is warranted.

4.4 Calcaneal Fracture Energy:

Patients with high-energy intra-articular calcaneal fractures face a poor prognosis with a significant risk of developing PTOA. Prior research has established a link between the energy involved in fracturing the tibial plafond and PTOA, and preliminary results suggest this relationship may exist in other joints. For this reason, the fracture energy metric was applied to high-energy intra-articular calcaneal fractures. It was hypothesized that higher energy calcaneal fractures would have poorer outcomes when compared with relatively lower energy fractures. This is the first opportunity for the fracture energy metric to be compared directly with a patient outcome metric. The Kellgren-Lawrence radiographic arthrosis grading scale or KL grade was chosen as the outcome metric because it offered the most objective metric for outcomes. While it doesn't directly relate to arthritis and arthritic pain, it is a good surrogate for arthritis as the radiographic changes it focuses on can precede pain and further joint degeneration.

The KL-grades of the fractures and the fracture energy metric were both compared with an established clinical metric in calcaneal fractures; the Sanders classification. Previous studies have demonstrated the effectiveness of the Sanders classification as a prognostic marker for long-term clinical outcomes of displaced intra-articular calcaneal fractures [52]. Therefore, associations between the Sanders classification and fracture energy would also be of note.

The results show a very weak association between the KL-grade and the fracture energy. The present clinical classification standard, the Sanders classification, also fails to demonstrate a strong correlation with KL-grade for this small series of cases. However, upon accounting for a known confounder, the post-reduction articular step-off,

a trend emerged. The pre-operative CT scans evaluated for fracture energy showed promise in predicting KL-grade and thus, PTOA development.

When compared to the clinical standard for evaluating calcaneal fractures, the Sanders classification, the objective CT-based fracture energy metric appears to be more predictive of PTOA risk. Residual step-off is likely a confounding variable when evaluating PTOA risk based upon radiographic evidence of PTOA development using the KL grade. It is also important to note that the minimum follow-up time included in this study is 18 months. PTOA is a progressive disease and as such more cases are likely to develop the disease and have poor outcomes and later dates. Additionally, many more cases will likely need to be analyzed before these types of relationships can begin to be adequately understood.

4.5 Fracture Energy Comparison:

While both proximal and distal fractures of the tibia can result in post-traumatic osteoarthritis development, plateau fractures have lower incidence of post-traumatic osteoarthritis when compared with plafond fractures. Reasons for this difference are not well understood, but it is known that differences in outcomes can be related to the acute amount of damage sustained at the time of injury. It stands to reason then that the fracture energy would be higher in the tibial plafond due to the increased incidence of PTOA compared with the plateau. However, the results do not support such a hypothesis. There was no discernable difference in the fracture energy range between the two fracture types. Thus, other factors exist that need to be considered upon interpretation of the results.

A major confounder stems from the quality of surgical reduction. Offsets in the joint congruity larger than 2 mm have been demonstrated to increase risk of PTOA at 2 years in the tibial plafond. However, the tibial plateau is thought to be generally more accepting of articular step-offs showing no statistically significant difference in outcomes in fractures with <3 mm of displacement [53]. This obfuscates the relationship between fracture energy and patient outcomes as articular step-off is shown to be an independent predictor of the differences in PTOA rates between the plafond and plateau. Further complicating this relationship is the fact that higher energy fractures typically have more complex fracture patterns and a greater degree of comminution. Both of which can make accurate surgical reductions more challenging thus resulting in larger step-offs. Therefore, the energy of the fractures may be predictive of the step-off which may be the true cause of observed differences in PTOA rates.

Further complicating the relationship are the differences in joint anatomy. The plafond injuries may simply be more difficult to accurately reduce to than plateau injuries. Other potential differences could stem from the size of the anatomy. The tibial plateau has a significantly larger articulating surface (1150 mm^2) than the tibial plafond (578±83 mm^2) [54, 55]. The joint therefore, could experience a higher energy per unit area transmitted upon fracturing leading to poorer outcomes.

Substantial differences in soft tissue structures also offer an anatomical explanation. The tibial plateau has a dense, load bearing, fibrocartilaginous meniscus and substantial soft tissue. It is reasonable to assume that in contrast with the robust bony load bearing in the ankle, the knee's soft tissues aid in preventing its degradation post-fracture despite similar energies involved in the injuries.

Calcaneal fractures included in this study were not chosen to span the spectrum of injury and only included Sanders class 2 through 4 injuries. Sanders classes 2 through 4 fractures are generally considered very severe injuries and thus, it was anticipated that the energy spectrum these injuries spanned would be smaller and higher in comparison to the tibial injuries. The results showed that the injuries observed did not span a large distribution of fracture energies and were focused on the higher end of the energy spectrum as anticipated.

The calcaneus is a relatively small, dense bone in comparison to the tibia. Therefore, it is possible that there is a lower ceiling or a higher floor for fracture energy in calcaneal injuries. Ongoing study of calcaneal fractures spanning a larger spectrum of injuries will enable a more complete picture of whether differences such as these exist between fractures of different bones and joints.

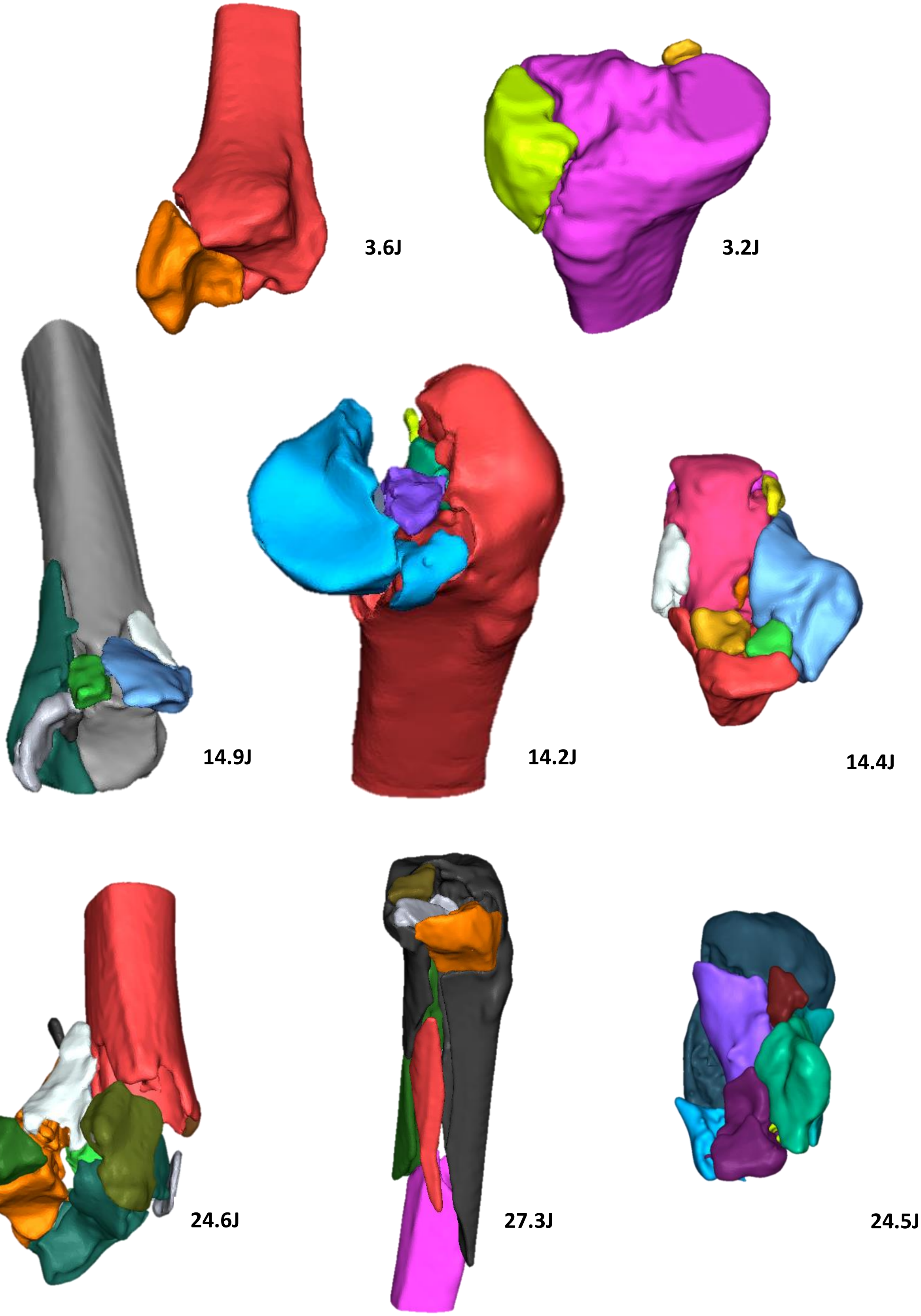


Figure 4-3: Fracture energy comparison between tibial plafond (left), plateau (middle), and calcaneal (right) injuries.

4.6 Limitations:

The methodology described in this work is not without limitations. Unlike the prior fracture energy work, the new methodology does not yet include an articular comminution metric. The articular comminution metric used previously combined with the fracture energy demonstrated excellent predictive capabilities. Additionally, in clinician evaluation of severity ranking for the plateau, orthopaedic surgeons judged the fracture severity based upon plain radiographs, and not on the CT scan data with which the fracture energy was evaluated. Therefore, it is possible that there were fracture characteristics that were not appreciated on the plain radiographs. This could have led to an underestimation of severity by surgeon assessment.

Further limitations stem from the speed and assumptions implicit in the methodology. Each fracture severity assessment required approximately 1 hour to complete. A vast majority of this time required significant user interaction in the segmentation and classification tasks. While it was faster than the previous fracture energy methodology’s 8-10 hour evaluation, it failed to achieve the speed (~15 minutes per fracture) of the previously expedited method. An invalid assumption inherent to the energy calculation is that bone is a brittle solid. Thus, this method does not account for any plastic deformation that might occur. Hence, impaction fractures may have absorbed energy not accounted for in the metric that lead to underestimation of injury severity.

4.7 Conclusions:

This thesis detailed the development of a fracture severity assessment methodology capable of being applied to any articular fracture. The methods were designed to reliably and objectively determine a physically meaningful property of fractures, the energy absorbed by the bone upon fracturing. It demonstrated substantial improvements over prior fracture energy assessment work. These improvements included reducing the time from 8-10 hours down to ~1 hour per case and more accurately representing fractured area energy release rates. The newly developed fracture severity assessment methods proved capable as a versatile gauge of injury severity in multiple joints. It was tested against clinician assessment in the tibial plateau and plafond, and was evaluated against present clinical severity systems in the plateau, plafond, and calcaneus. It demonstrated good agreement with both clinician assessment and clinical severity classification systems. It also demonstrated predictive capabilities in calcaneal fractures for patient outcomes. In conclusion, while the objective CT-based measurement of fracture energy showed promise, ongoing work will determine the extent of its clinical utility.

4.8 Future Directions:

Future directions for this work include implementing additional physically meaningful objective measures of injury severity. One such measure could be of the articular fracture edge length. The 3d interface of the fracture classification system presented in this work as well as boundaries between the fractured and intact bone could be leveraged to identify fractures along the articular surface and quantify their length. This is meaningful as it is known that chondrocyte death is elevated along articular fracture edges [56]. This chondrocyte death and therefore fracture edge length have the potential be useful in prediction of PTOA. Additional physical measures with such potential also exist like the degree of articular comminution and the amount of fragment displacement. Objective quantification and combination of these measures offers promising future research directions.

Another promising area for improvement is in the segmentation task. Segmentation and model creation required ~75% of the time spent on each case to complete. This leaves potential for substantial increases in the speed of metric evaluation when coupled with continually improving classification training sets. The ultimate goal of such improvements would be to achieve clinically relevant analysis on a clinically relevant time scale. Thus, allowing clinicians to have access to the energies involved in patient injuries helping to guide assessment of injury severity.

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Objective Metric of Energy Absorbed in Tibial Plateau Fractures Corresponds Well to Clinician Assessment of Fracture Severity

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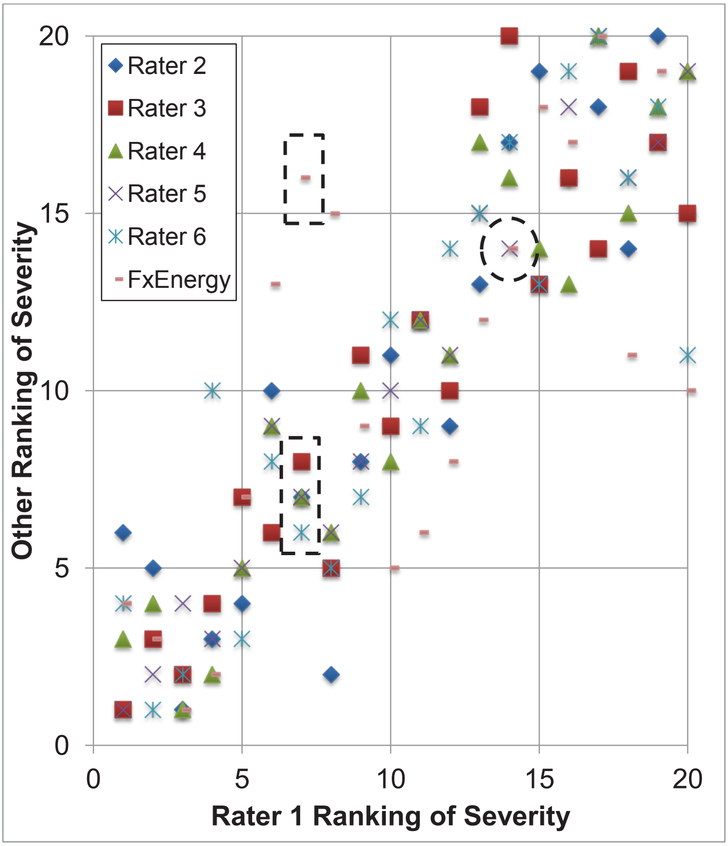
Background/Purpose: Outcomes of intra-articular fractures are influenced both by acute mechanical damage and by residual chronic changes in joint loading. The extent of damage sustained in the acute setting reflects the energy absorbed in creation of the fracture; therefore, fracture energy can be expected to substantially influence clinical outcomes. Previous investigations have demonstrated that objective CT-based quantification of fracture energy in pilon fractures correlates with surgeon assessment of injury severity and 2-year radiographic outcomes. It is not clear whether these findings can be extrapolated to other articular fracture types. In this work, we explored whether this technique of fracture energy measurement could be used to stratify the severity of tibial plateau fractures. Specifically, we hypothesized that a CT-based measure of fracture energy would correspond to subjective surgeon assessment of fracture severity. We tested the hypothesis by comparing surgeon rank ordering of fracture severity for a series of tibial plateau fractures with CT-based measurements of fracture energy.

Methods: Twenty fractures were selected from a series of 50 tibial plateau fractures to span a full spectrum of severity. Fracture classification ranged from OTA 41-B1 to 41-C3. Six fellowship-trained orthopaedic trauma surgeons independently rank-ordered the fractures in order of severity using AP and lateral knee radiographs. The only instructions given to the raters were to rank the cases in order of least to most severely injured. Subjectively, they used the number and size of fragments, the amount and direction of displacement, percentage of articular surface involved, and whatever other features they felt were important based on their clinical experience. CT-based image analysis techniques were used to quantify the fracture energy. The software identifies all fracture fragments on CT imaging and calculates the amount of bone surface area liberated by the fracture. The previously validated algorithm incorporates fracture liberated surface area and bone density to provide the fracture energy measurement. The agreement between fracture severity assessments made by the surgeons and the ranking by fracture energy measurement was tested by computing their concordance. A pair of cases' injury severity rankings was deemed concordant if the case with the higher ranking of injury severity for one rater also had the higher ranking for a second rater. Simply put, the rate of concordance is the number of concordant pairs divided by the total number of possible pairings.

Results: Concordance between the six orthopaedic surgeons ranged from 82% to 93%. Concordance between surgeon severity ranking and fracture energy ranged from 73% to 78% (Fig. 1).

See pages 47 - 108 for financial disclosure information.

Figure 1: Representative rank-ordering of fracture severity by six orthopaedic trauma surgeons and by fracture energy. The y-axis represents severity ranking as assigned by raters 2-6 and according to the calculated fracture energy. The x-axis represents the rank ordering of rater 1. As an example, there was high agreement between rater 1 and raters 2 – 6 at rater-1 injury number 7, but this fracture's rank according to fracture energy calculation was much higher (black dashed boxes). At rater-1 injury number 14, the rank according to fracture energy was the same as the rank assigned by raters 1 and 5 (dashed circle).



Conclusion: There is a high level of agreement between surgeon assessment of tibial plateau fracture severity and CT-based measurement of fracture energy. In addition, agreement among six surgeons with extensive clinical experience judging injury severity was excellent. Taken together, these results confirm that a CT-based method of calculating fracture energy accurately portrays fracture severity as judged clinically for tibial plateau fractures and provides an objective way to quantify injury severity. In addition, it is likely this tool will be clinically useful as there was excellent surgeon agreement on fracture severity. Further research is ongoing to characterize the relationship between fracture energy and clinical outcomes. Funding: Research reported in this abstract was supported by the National Institute of Arthritis and Musculoskeletal and Skin Diseases of the National Institutes of Health under award number R21AR061808. The research was also aided by a grant from the Foundation for Orthopaedic Trauma.

PAPER NO. 044

Energy Absorbed in Fracturing is Similar in Tibial Plateau and Pilon Fractures Over a Full Spectrum of Severity

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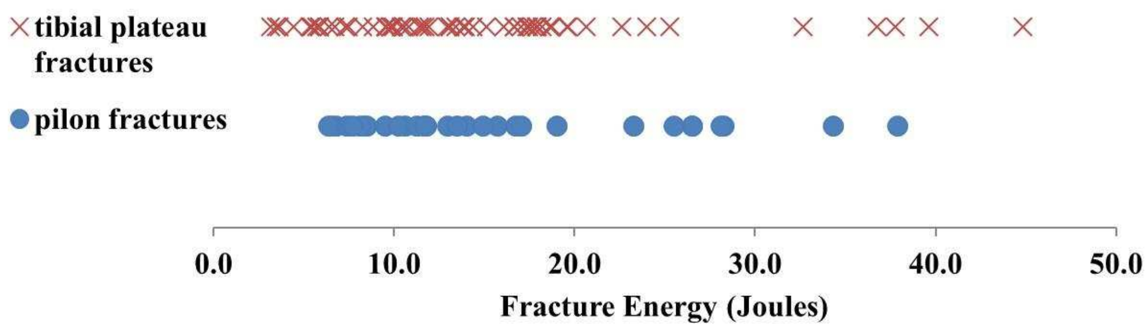
INTRODUCTION: Tibial pilon fractures have a higher rate of post-traumatic osteoarthritis (PTOA) compared to tibial plateau fractures. The reasons for this difference are not understood. Outcomes of articular fractures are influenced by acute damage sustained at the time of injury and residual abnormal loading resulting from changes in congruity, alignment, or stability after healing. One potential explanation for the outcome differences between these two fracture types is that greater energy of injury is absorbed to create tibial pilon fractures compared to plateau fractures. In this study, we utilized a CT-based measurement of fracture energy to explore the hypothesis that fracture energy is consistently higher in pilon fractures compared to plateau fractures.
METHODS: Fifty-nine tibial plateau fractures (OTA 41-B1 to 41-C3) from a multi-institutional study were specifically selected to span an entire spectrum of injury severity. These were compared with 31 tibial pilon fractures (43-B1 to 43-C3) selected in a similar manner. Fracture energy was calculated using a previously validated CT-based image analysis technique. This was accomplished using specialized software, which identifies all fracture fragments on CT imaging and calculates the amount of free bone surface area generated by the fracture. This surface area and a CT-based metric of bone density are incorporated into an algorithm to calculate fracture energy. Fracture energy values computed for the plateau fractures were compared to those of pilon fractures.
RESULTS: The range of fracture energies for tibial plateau fractures was 3.1 J to 44.9 J (Figure 1). The range of fracture energies for pilon fractures was 6.4J to 37.9 J. The relative distributions of fracture energies within the spectrum for each fracture type were similar.
CONCLUSIONS: There were no discernible differences in fracture energy range between the two fracture types, refuting our hypothesis. Similar injury mechanisms typically lead to these two fractures, and previous studies show substantially lower incidences of PTOA resulting from tibial plateau fractures compared to pilon fractures. The findings in this study showing similar energy absorption profiles suggest that the tibial plateau may be more tolerant of impact injury compared to the distal tibia. Additionally, differences in clinical outcomes between the two fracture types are likely not attributable to differences in the fracture energy. PTOA represents an organ-level injury response that is complex and likely joint-specific. Impact tolerance of the proximal tibia may be better explained by differences in cartilage thickness, the inflammatory response after injury, mechanics of joint load distribution, or a variety of other factors. Research reported in this abstract was supported by the National Institute of Arthritis and Musculoskeletal and Skin Diseases of the National Institutes of Health under award number

R21AR061808. The research was also aided by a grant from the Foundation for Orthopaedic Trauma (FOT).

Figure 1: Tibial plateau and pilon fracture energy value distributions over a full spectrum of injury severity



POSTER NO. P511

CT-Based Metric of Tibial Plateau Fracture Energy Corresponds Well to Clinician Assessment of Fracture Severity

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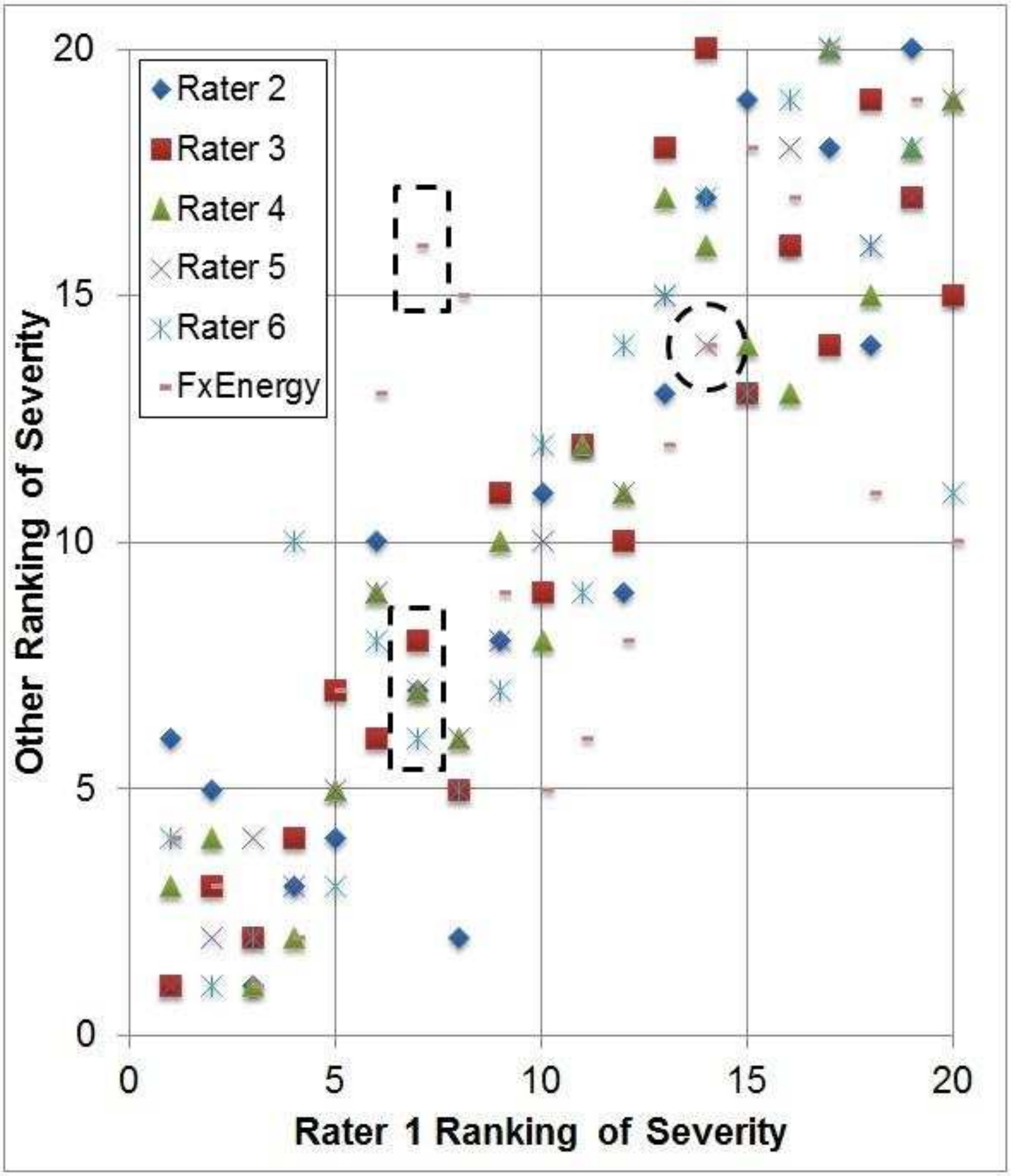
INTRODUCTION: Outcomes of intraarticular fractures are influenced both by acute mechanical damage and by residual chronic changes in joint loading. The extent of damage sustained in the acute setting reflects the energy absorbed in creation of the fracture; therefore, fracture energy can be expected to substantially influence clinical outcomes. Previous investigations have demonstrated that objective CT-based quantification of fracture energy in pilon fractures correlates with surgeon assessment of injury severity and two-year radiographic outcomes. It is not clear whether these findings can be extrapolated to other articular fracture types. In this work, we explored whether energy measurement could be used to stratify the severity of tibial plateau fractures. Specifically, we hypothesized that a CT-based measure of fracture energy corresponds to subjective surgeon assessment of fracture severity. We tested the hypothesis by comparing surgeon rank ordering of fracture severity for a series of tibial plateau fractures with CT-based measurements of fracture energy.
METHODS: Twenty fractures were selected from a series of 50 tibial plateau fractures to span a full spectrum of severity. Fracture classification ranged from OTA 41-B1 to 41-C3. Six fellowship-trained orthopaedic trauma surgeons independently rank-ordered the fractures in order of severity using AP and lateral knee radiographs. The raters were instructed to rank the cases in order of least to most severely injured. Subjectively, they used the number and size of fragments, fracture displacement, portion of articular surface involved, and any other features they felt were clinically important. Previously validated, CT-based image analysis software was used to quantify fracture energy based on the amount of bone surface area liberated by the fracture and bone density. The agreement between fracture severity assessments made by the surgeons and the ranking by fracture energy measurement was tested by computing their concordance. A pair of cases' injury severity rankings was deemed concordant if the case with the higher ranking of injury severity for one rater also had the higher ranking for a second rater. Simply put, the rate of concordance is the number of concordant pairs divided by the total number of possible pairings.
RESULTS: Concordance between the six orthopaedic surgeons ranged from 82% to 93%. Concordance between surgeon severity ranking and fracture energy ranged from 73% to 78%. See Figure 1.
CONCLUSIONS: There is a high level of agreement between surgeon assessment of tibial plateau fracture severity, and CT-based measurement of fracture energy. In addition, agreement among six surgeons with extensive clinical experience judging injury severity was

excellent. Taken together, these results confirm that a CT-based method of calculating fracture energy accurately portrays fracture severity as judged clinically for tibial plateau fractures and provides an objective way to quantify injury severity. Research reported in this abstract was supported by the National Institute of Arthritis and Musculoskeletal and Skin Diseases of the National Institutes of Health under award number R21AR061808. The research was also aided by a grant from the Foundation for Orthopaedic Trauma (FOT).

Figure 1: Representative rank-ordering of fracture severity by six orthopaedic trauma surgeons and by fracture energy. The y-axis represents severity ranking as assigned by raters 2-6 and according to the calculated fracture energy. The x-axis represents the rank ordering of rater 1. As an example, there was high agreement between rater 1 and raters 2 – 6 at rater-1 injury number 7, but this fracture's rank according to fracture energy calculation was much higher (black dashed boxes). At rater-1 injury number 14, the rank according to fracture energy was the same as the rank assigned by raters 1 and 5 (dashed circle).



Quantifying tibial plateau fracture severity: fracture energy agrees with clinical rank ordering

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Disclosures: None

INTRODUCTION: Outcomes of intraarticular fractures are influenced both by acute mechanical damage and by residual chronic changes in joint loading. The amount of energy dissipated in the creation of a fracture (i.e., the fracture energy) is a physical manifestation of the fracture severity, and it significantly influences outcomes; fracture energy in pilon fractures correlates with surgeon assessment of injury severity and two-year radiographic outcomes [1]. It is not clear whether these findings can be extrapolated to other articular fracture types. In this work, we explored whether this technique of objective fracture energy measurement could also be used to stratify the severity of tibial plateau fractures in a manner that would agree with expert opinions of fracture severity. We hypothesized that an objective CT-based measure of fracture energy would correspond to subjective surgeon assessment of fracture severity.

METHODS: A fellowship-trained orthopaedic trauma surgeon selected 20 cases from a series of 50 consecutive tibial plateau fractures to span a full spectrum of fracture severity and to avoid having multiple fractures cluster around a common level of severity. Fracture classifications included OTA 41-B3 and 41-C3. Patients sustaining the fractures ranged in age from 18 to 70-years-old. There were 12 males and 8 females. Our Institutional Review Board approved use of the patient data. Six fellowship-trained orthopaedic trauma surgeons from four separate institutions independently rank-ordered the fractures in order of severity based upon the appearance of the fractures in AP and lateral knee radiographs. The raters were instructed to rank the cases in order of least to most severely injured. A previously validated CT-based image analysis approach was used to quantify the fracture energy based upon measurement of the fracture-liberated surface area and accounting for bone density (Figure 2) [1,2,3]. The agreement between fracture severity assessments made by the surgeons and the ranking by fracture energy measurement was tested by computing their concordance, a statistical measure that estimates the probability that any two cases would be ranked with the same ordering by two different raters or methods. A pair of cases' injury severity rankings was deemed concordant if the case with the higher ranking of injury severity for one rater also had the higher ranking for a second rater, and the concordance was calculated as the number of concordant pairs divided by the total number of possible pairings.

RESULTS: Fracture energies ranged from 5.46 J to 36.73 J. There was a high level of agreement between the six experienced surgeons in their assessments of tibial plateau fracture severity (Figure 1), with concordance between the six ranging from 82% to 93% (mean of 85%). The concordance between surgeon severity rankings and the fracture energy severity ranking were slightly less high, ranging from 73% to 78% (mean of 74%). Despite the good overall agreement observed between surgeon assessments of fracture severity and the fracture energy metric, there were some notable exceptions.

DISCUSSION: The purpose of this study was to determine whether a CT-based fracture energy metric could provide an objective, quantifiable measure of tibial plateau fracture severity by comparing it to the current gold standard, subjective expert surgeon opinion. We found a high level of agreement (85%) regarding fracture severity among the six orthopaedic trauma subspecialists. The level of agreement between surgeon assessments of fracture severity and fracture energy was not as high (74%), but still much better than chance concordance (50%). These results demonstrate that fracture energy reasonably captures expert opinion regarding the relative fracture severity over a full spectrum of tibial plateau fractures.

SIGNIFICANCE: This result provides support for further utilization of an objective CT-based method for determining injury severity.

REFERENCES: (1) Thomas TP, et al. *J Orthop Trauma* 24:764-8, 2010. (2) Beardsley CL, et al. *J Biomech* 35:331-8, 2002. (3) Anderson DD, et al. *J Orthop Res* 26:1046-52, 2008.

ACKNOWLEDGEMENTS: The research reported in this abstract was supported by the National Institute of Arthritis and Musculoskeletal and Skin Diseases of the National Institutes of Health under award numbers P50 AR055533 and R21 AR061808, as well as by a grant from the Foundation for Orthopaedic Trauma.

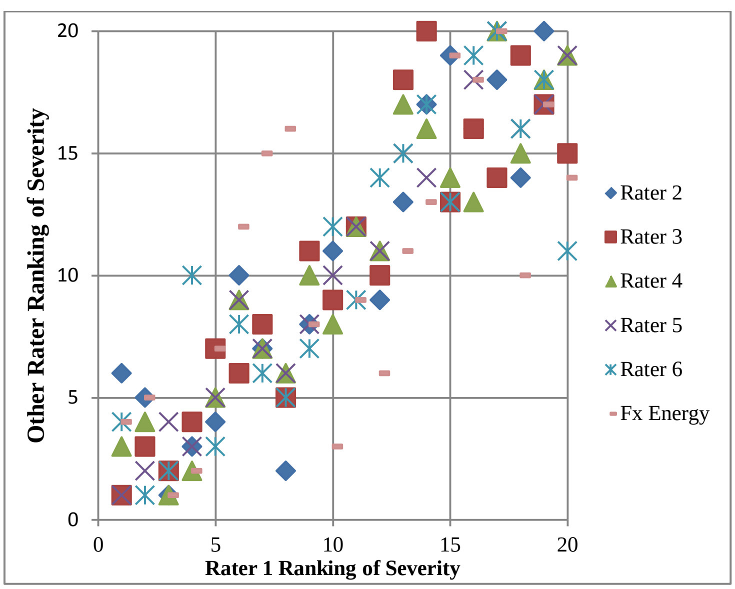

Figure 1: Representative rank-ordering of fracture severity by six orthopaedic trauma surgeons and by fracture energy.

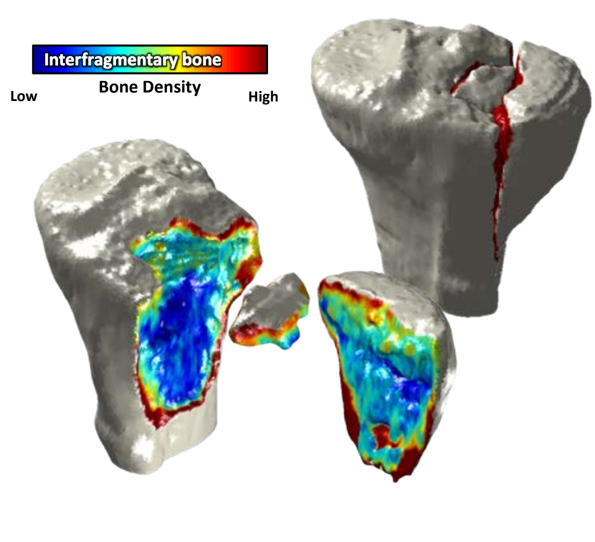

Figure 2: Interfragmentary surface classification for a Schatzker II fracture with a fracture energy of 8.7 J

Objective fracture energy assessment of tibial plateau fractures loosely corresponds to Schatzker classification

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Disclosures: None

INTRODUCTION: The Schatzker system for classifying tibial plateau fractures was developed as a method for identifying groups of fractures with distinct pathomechanical and etiological factors [1]. Its utility in guiding treatment and predicting outcomes is well established [2], but its accuracy in stratifying the severity of a tibial plateau fracture has never been assessed. The Schatzker system is subjective, and it suffers from poor inter-observer reliability (kappa values from 0.38 to 0.68) [3]. For these reasons, an objective CT-based fracture severity metric has been adapted to assess the energy involved in the fracture creation mechanism [4]. The present study aimed to compare the Schatzker classification of tibial plateau fractures with this objective fracture energy metric to determine how well the classification system captures the energy required to produce a fracture.

METHODS: A series of forty patients with tibial plateau fractures, ranging from Schatzker I to VI, were consented for this study. Pre-operative CT scans were used to assess injury severity. A CT-based image analysis methodology was utilized to objectively determine fracture energy based upon the amount of bone surface area liberated by the fracture and accounting for differences in bone density [4,5,6]. Figure 2 demonstrates both the identification of the interfragmentary bone surfaces and the bone density variation. The agreement between the objective fracture energy metric and the Schatzker classification was assessed based upon the concordance in the data. A pair of cases was deemed concordant if the case with the higher fracture energy also had a higher Schatzker classification, and the concordance metric was calculated as the number of concordant pairs divided by the total number of possible pairings.

RESULTS: The average fracture energy monotonically increased with increasing Schatzker classification (Figure 1), indicating general agreement between the fracture patterns defined by Schatzker and the energy required to produce such fractures. However, the fracture energies varied, in some instances considerably, within the Schatzker classes. The concordance between the Schatzker classification and the objective fracture energy metric was 70.6%.

DISCUSSION: Fractures of the medial tibial plateau (Schatzker IV and V) are generally considered to be more severe, with poorer outcomes when compared to lateral (Schatzker I and II) fractures. The present data suggest that the fracture energy may partly explain these differences in outcomes. Additionally, each Schatzker class included a range of energies, with a large degree of overlap between all categories. High-energy fractures in lower classes may also explain outliers in previous data sets that have relied on Schatzker classification as a surrogate for injury severity.

SIGNIFICANCE: The findings of this study suggest that the Schatzker classification is partially representative of the energy that created the fracture but does not capture the range of injury severities within each category. A CT-based fracture energy metric combined with the Schatzker classification may offer advantages of both the anatomic characterization of injury location and an objective assessment of the energy of injury.

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Figure 1: Schatzker Classification vs Fracture Energy with averages by classification (indicated by red boxes).

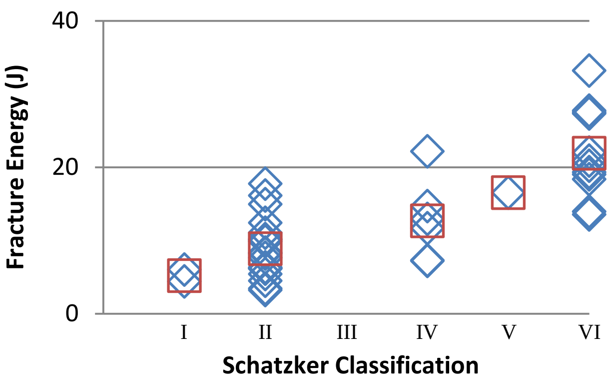
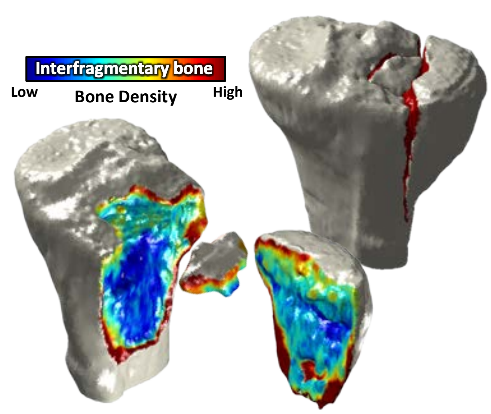


Figure 2: Interfragmentary surface classification for a Schatzker II fracture with a fracture energy of 8.7 J



Relating Fracture Severity to Post-Traumatic Osteoarthritis Risk after Intra-Articular Calcaneal Fractures

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Disclosures: K. Rao: None. K. Dibbern: None. P. Phisitkul: None. J. Marsh: None. D.D. Anderson: None.

INTRODUCTION: Patients with high-energy intra-articular fractures (IAFs) face a poor prognosis and a significant risk of developing disabling post-traumatic osteoarthritis (PTOA). Objective CT-based measures of fracture energy have been used to link fracture severity to PTOA risk following IAFs of the distal tibia [1-3], but have never been applied to the calcaneus. The Sanders classification is used as a prognostic marker for long-term clinical outcomes [4] but has not been correlated with fracture energy. The purpose of this study was to establish the relationships between the Sanders classification, fracture energy, the quality of the surgical reduction, and PTOA development in patients with intra-articular calcaneal fractures.

METHODS: Eighteen patients with nineteen intra-articular calcaneal fractures were consented for this IRB approved this study. The patients were selected as a sample of convenience from a series of 120 cases that have been identified and are being followed. All patients were treated with percutaneous reduction and screw fixation. Standard of care pre-op CT scans were used to classify the fractures according to the Sanders classification and to assess their severity. The Sanders classification for calcaneal fractures is based on coronal and axial CT scan sections, where type I are non-displaced IAFs; type II are two-part or split fractures of the posterior facet; type III are three-part fractures of the posterior facet (with two fracture lines and a centrally depressed fragment); and type IV are comminuted fractures [5]. Fracture severity was quantified by fracture energy, which is proportional to the fracture-liberated surface area of bone [1, 6-7]. A CT-based image analysis methodology was used to identify and measure the inter-fragmentary surface area (Figure 1). The liberated surface area was multiplied by the energy release rate, scaled by CT intensities to account for variation in bone density, to calculate the fracture energy [2,7]. Three experts independently measured the maximum articular step-off, a measure of the quality of surgical reduction, visualized on a post-op CT. PTOA development was graded using the Kellgren-Lawrence (KL) scale for all patients with a follow up time > 18 months. Because the measures to be compared mix ordinal and continuous values, agreement was assessed using concordance—the probability that the fracture energies correctly discriminate between pairs of Sanders classification and/or KL scores.

RESULTS: The nineteen calcaneal fractures analyzed for fracture severity ranged from Sanders class II to IV. Their fracture energies ranged from 12.3 to 24.5 J (mean ± standard deviation = 18.0 ± 2.9 J). A concordance of 0.75 was observed between Sanders classification and fracture energy. Ten patients with eleven intra-articular fractures were assessed for PTOA development, based on a follow up time > 18 months. For those ten patients, the most recent follow-up radiographs available were obtained between 20 and 74 months post-injury. There was a complex relationship observed between fracture energy, Sanders classification, articular step-off, and KL grade. When cases were segregated based on the articular reduction obtained being less than 2 mm, a pattern of increasing PTOA risk with increasing fracture energy emerged (Figure 2). There was no such relationship observed between Sanders classification and KL grade.

DISCUSSION: The results suggest that fracture severity is more predictive of PTOA risk than is the Sanders fracture classification. The residual articular step-off is a likely confounder influencing PTOA risk when evaluating fracture energy vs KL grade. Cases with an articular step-off < 2 mm demonstrated a positive association between fracture energy and risk of PTOA. Due to a small sample size, statistical significance could not be conclusively established.

SIGNIFICANCE: These data suggest that higher initial injury severity as assessed by an objective metric could predict an increased risk of PTOA. This has implications for evaluation and treatment of calcaneal fractures with the aim of forestalling PTOA.

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ACKNOWLEDGEMENTS: The research reported in this abstract was supported by the National Institute of Arthritis and Musculoskeletal and Skin Diseases of the National Institutes of Health under award number P50 AR055533 and by a Summer Research Fellowship from the University of Iowa Carver College of Medicine. The assistance of Saran Tantavisut, MD and Brian Westerlind in data collection is also gratefully acknowledged.

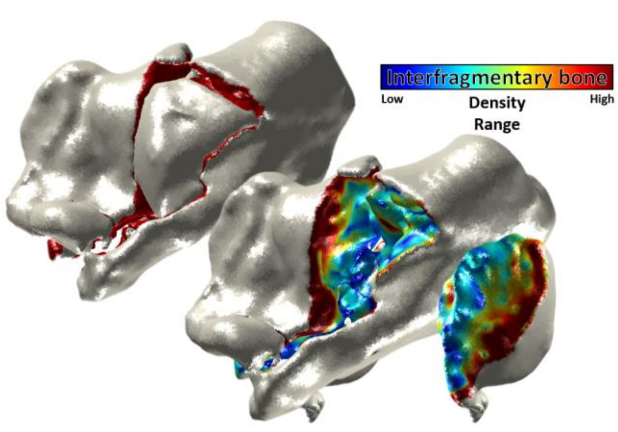

Figure 1. 3D model of a Sanders class III intra-articular calcaneal fracture. Left: inter-fragmentary surface area (red). Right: inter-fragmentary bone with energy density range.

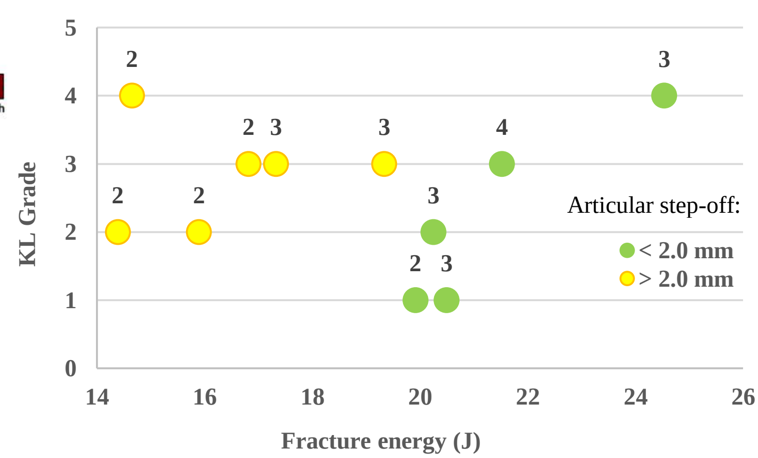

Figure 2. Fracture energy vs KL Grade. Number above data points indicates Sanders classification.

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Elevated Contact Stress after Surgical Reduction of Acetabular Fractures Correlates with Progression to Post-Traumatic Osteoarthritis

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INTRODUCTION

Residual incongruity following surgical reduction of acetabular fractures is associated with post-traumatic osteoarthritis (PTOA) [1]. Malreduction greater than 2mm is considered significant. Despite advances in reduction and fixation strategies over the past two decades, there remains a significant prevalence of PTOA in patients that suffer from acetabular fractures [1]. The strong association of PTOA to subtle fracture malreduction suggests that the joint degeneration has a mechanical origin. Elevated joint contact stress, as is often found with fracture malreduction, has previously been demonstrated to predict PTOA development in the distal tibia [2]. Despite this strong mechanical association of elevated contact stress with PTOA progression, this relationship has not yet been investigated in patients after acetabular fractures. The goal of this study was to determine if contact stress elevation following surgical fracture reduction is related to PTOA incidence in patients with acetabular fractures.

METHODS

In this study, a series of 11 patients with surgically reduced acetabular fractures were retrospectively studied. These patients were the first to be analyzed from a larger series of patients being studied. The average patient age was 43.3 years (range: 27-69 years). Patient-specific geometries of hip joints were segmented from post-operative CT-scans and utilized to perform computational contact stress analysis through a previously validated discrete element analysis (DEA) methodology [3]. Contact stresses were computed at heel-strike, mid-stance, and toe-off stages of the gait cycle to determine the maximum contact stress at critical points in gait. The overall average maximum contact stress for each case was determined by taking the mean of these maximum contact stress values. Patient outcomes were evaluated by the Kellgren-Lawrence arthrosis grade (KL grade) from follow-up weight-bearing radiographs obtained at a minimum follow-up of two years (range: 27-68 months).

RESULTS AND DISCUSSION

All fractures had at least 2mm of malreduction on post-operative CT scans. The average maximum acetabular contact stresses ranged from 5.2 to 21.7 MPa. KL grades ranged from 0 (no PTOA) to 4 (significant PTOA). There was a strong positive correspondence between maximum contact stress and KL grade (Figure 1). The three patients with the lowest maximum contact stress (range: 5.2 to 8.4 MPa) had the lowest KL grade of 0, while the 4 cases with the highest maximum contact stress (19.5 to 21.7 MPa) had a KL grade of 4.

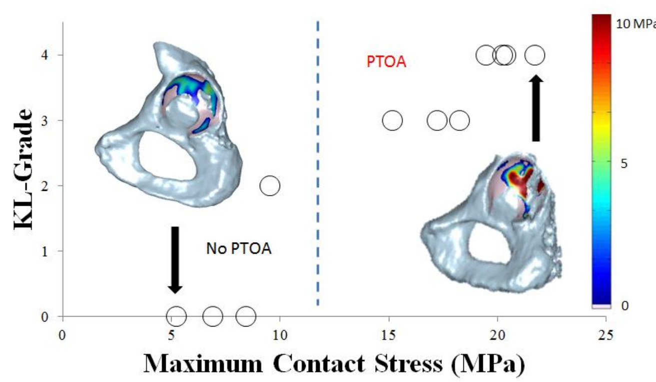

Figure 1. KL grade vs. maximum contact stress at greater than two year follow-up.

Of the 11 acetabular fracture patients analyzed, 7 had developed PTOA of the hip (KL grade > 2) and an average maximum contact stress of greater than 10 MPa. The other four patients did not develop PTOA (KL grade ≤ 2), further demonstrating the strong relationship between contact stress and PTOA. Five patients, with maximum contact stresses ranging

from 15.1 to 21.7 MPa, had been converted to a total hip arthroplasty. Table 1, below, shows the outcome for each patient as well as the average maximum contact stress computed in each hip.

CONCLUSIONS

This series of patients, the first to be analyzed from a larger series, demonstrate a strong relationship between post-operative elevated contact stresses and progression to PTOA in patients that undergo surgical reduction of acetabular fractures. These results support clinical observations that malreduction of acetabular fractures leads to a high rate of joint failure. Our series of patients demonstrated that joint contact stress exceeding approximately 10 MPa resulted uniformly in PTOA. This is comparable to thresholds for joint contact stresses that predictably lead to PTOA in articular fractures of other lower extremity joints [2].

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Table 1: Average maximum contact stresses for each stage of gait cycle recorded for each case and additional case information used for data.

Average Maximum Contact Stress	Total Hip Replacement	PTOA development	KL grade
5.19	No	No	0
6.91	No	No	0
8.42	No	No	0
9.53	No	No	2
15.14	Yes	Yes	3
17.22	Yes	Yes	3
18.24	No	Yes	3
19.48	No	Yes	4
20.25	Yes	Yes	4
20.39	Yes	Yes	4
21.73	Yes	Yes	4

Clinical Fractures of the Tibial Plateau Involve Similar Energies as the Tibial Pilon

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INTRODUCTION

Post-traumatic osteoarthritis (PTOA) frequently occurs secondary to joint injuries, with articular fractures in the lower extremity particularly at risk. Despite similar injury mechanisms, incidence of PTOA is much higher in patients with fractures of the tibial pilon (74%) than those with fractures of the tibial plateau (22-44%).[1-2] The reasons for this difference are not well understood.[3] Surgeons have adopted fracture severity assessment methods to aid in treatment decision-making. However, conventional systems for classifying fractures are highly subjective, have poor reproducibility, and cannot reliably predict PTOA.[4]

Fracture severity can be objectively assessed using the amount of energy absorbed in fracturing a bone (i.e. fracture energy). In tibial pilon fractures, fracture energy is significantly correlated with PTOA incidence.[5] This study used an objective CT-based methodology for measuring fracture energy to explore the hypothesis that fracture energies are higher in pilon fractures compared to plateau fractures. The relationship between fracture energy and present clinical fracture classification systems was also explored to determine how well classifications reflect severity.

METHODS

Fellowship-trained orthopaedic trauma surgeons enrolled 75 patients with tibial plateau fractures and 52 patients with tibial plafond fractures. Fracture energies were calculated using a previously validated, objective, CT-based image analysis methodology (Figure 1). [5]

The fractures were also characterized according to the AO/OTA fracture classification system by three fellowship-trained orthopaedic traumatologists. The AO/OTA classification seeks to categorize fractures based upon morphological characteristics in order of increasing complexity and severity, where severity "implies anticipated difficulties of treatment, the likely complications, and the prognosis." [6]

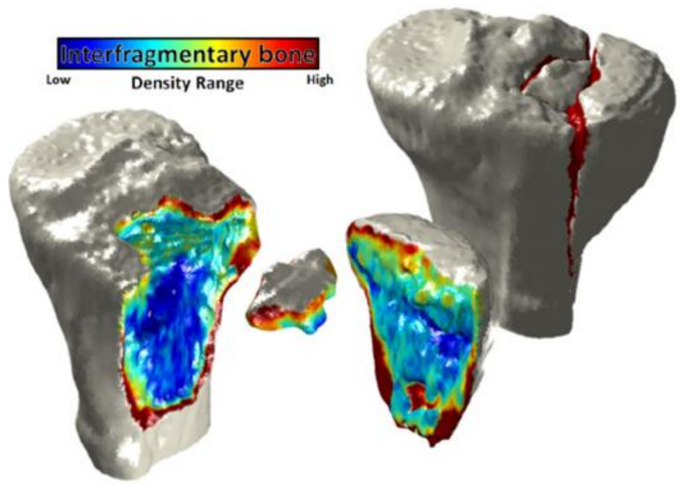

Figure 1. The surface area generated from the fracture (fracture-liberated surface area) and the bone densities across that surface were used to calculate fracture energy.

RESULTS

The range of fracture energies measured for tibial plateau fractures was 3.2 to 33.2 (13.3±6.8) Joules and 3.6 to 32.2 (14.9±7.1) Joules(J) for tibial pilon fractures. AO/OTA fracture classifications ranged from 41-B1 to 41-C3 and the pilon fractures ranged from 43-B1 to 43-C3. The distribution of energies within the spectrum for each fracture class was similar. The average fracture energies for the most part increased with increasing AO/OTA classification indicating a loose general agreement on severity (Figure 2).

DISCUSSION

There were no discernible differences in fracture energy range or distribution between plateau and pilon fracture types, refuting our original hypothesis. Similar injury mechanisms typically lead to these two fractures, and previous studies

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show a substantially lower incidence of PTOA resulting from plateau fractures compared to pilon fractures. Impact tolerance in the proximal tibia may be better explained by differences in morphology/anatomy, cartilage thickness, joint mechanics, or a variety of other factors.[7,8]

The larger range of fracture energies seen in higher classes of fracture energies may reflect the fact that more complex and variable injuries make up these classes. However, the higher class fracture patterns were not necessarily more severe (i.e., did not always have higher fracture energies). This suggests that fracture classifications are less reflective of severity for more complex fracture patterns. A surprisingly wide range of fracture energy was seen for the fracture classifications assessed. This suggests that these classifications are not a reliable surrogate for fracture severity. Combining fracture classification, which captures the morphologic characteristics of the fracture, with objective measurement of fracture energy would provide a more complete assessment of articular fractures.

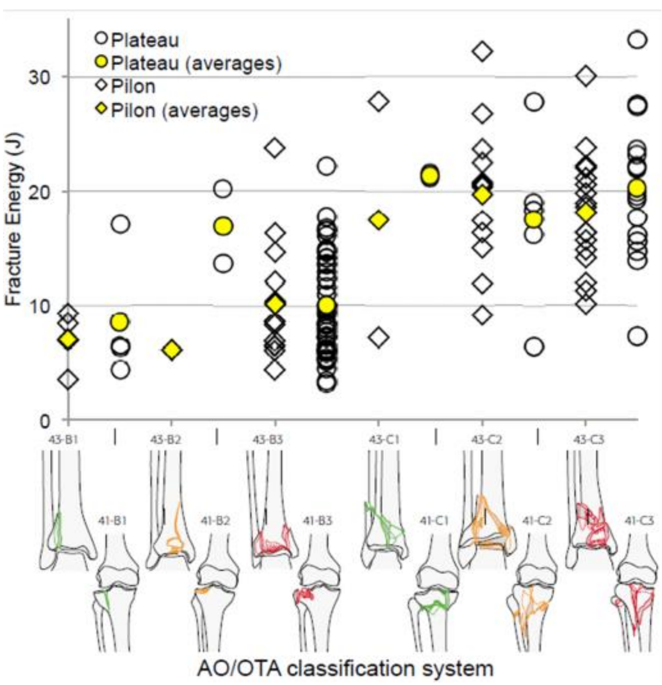

Figure 2. Range of fracture energies as they vary over the different AO/OTA classes for the tibial plateau and pilon fractures.

CONCLUSIONS

Historically, studies comparing different groups of fractures have used AO/OTA fracture classification to show that the groups had similar fracture characteristics and severity. Perhaps the most useful conclusion from these data is that prior studies failing to demonstrate group equivalence simply by showing no statistical difference in fracture classification type are missing critical information about underlying differences in fracture severity. Assigning "high energy" and "low energy" based on injury mechanism and fracture pattern is largely subjective and fails to sufficiently stratify severity. The data presented in this study provide strong evidence of the utility that fracture energy has in the context of clinical research.

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Post-Traumatic OA Risk Relative to Intra-Articular Calcaneal Fracture Severity

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PURPOSE: Patients with high-energy intra-articular fractures (IAFs) face a significant risk of post-traumatic osteoarthritis (PTOA). Objective CT-based measures of fracture energy have been used to link fracture severity to PTOA risk following IAFs of the distal tibia [1-3] but not the calcaneus. The Sanders classification is used as a prognostic marker for long-term clinical outcomes [4] but has not been correlated with fracture energy. The purpose of this study was for the first time to objectively measure fracture energy in a series of calcaneal fractures and to establish the relationships between it and the Sanders classification, the quality of the surgical reduction, and clinical outcome in patients with intra-articular calcaneal fractures.

METHODS: Eighteen patients with nineteen IAFs of the calcaneus were consented for this IRB-approved study; they are the first to be analyzed from a series of 120 cases treated with percutaneous reduction and screw fixation that have been identified and are being followed. Pre-op CT scans were used to classify fractures according to Sanders et al. [5] and to assess their severity. Fracture severity was quantified by computing fracture energy using a CT-based image analysis methodology. [2] Three experts independently measured the maximum articular step-off from post-op CT. PTOA development was graded using the Kellgren-Lawrence (KL) scale and outcomes were assessed with VAS pain scores for patients with >18 month follow up. Because the measures to be compared mix ordinal and continuous values, agreement was assessed using concordance – the probability that the fracture energies correctly discriminate between pairs of Sanders classification and/or KL scores.

RESULTS: The nineteen calcaneal fractures analyzed for fracture severity ranged from Sanders class II to IV. Their fracture energies ranged from 12.3 to 24.5 J. A concordance of 0.75 was observed between Sanders classification and fracture energy. Ten patients with eleven intra-articular fractures were assessed for PTOA development, based on a follow up time > 18 months (range: 20 to 74 months) post-injury. There was a complex relationship observed between fracture energy, Sanders classification, articular step-off, and KL grade. Interestingly, for those cases having an articular step-off < 2 mm, PTOA risk increased with fracture energy (Figure 1). There was no such relationship observed between Sanders classification and KL grade.

CONCLUSION: The results suggest that fracture severity is more predictive of PTOA risk than is the Sanders classification. The residual articular step-off is a likely confounder influencing PTOA risk when evaluating fracture energy vs KL grade. Due to a small sample size, statistical significance could not yet be conclusively established. These data suggest that higher initial injury severity as assessed by an objective metric could predict an increased risk of PTOA. This has implications for evaluation and treatment of calcaneal fractures with the aim of forestalling PTOA.

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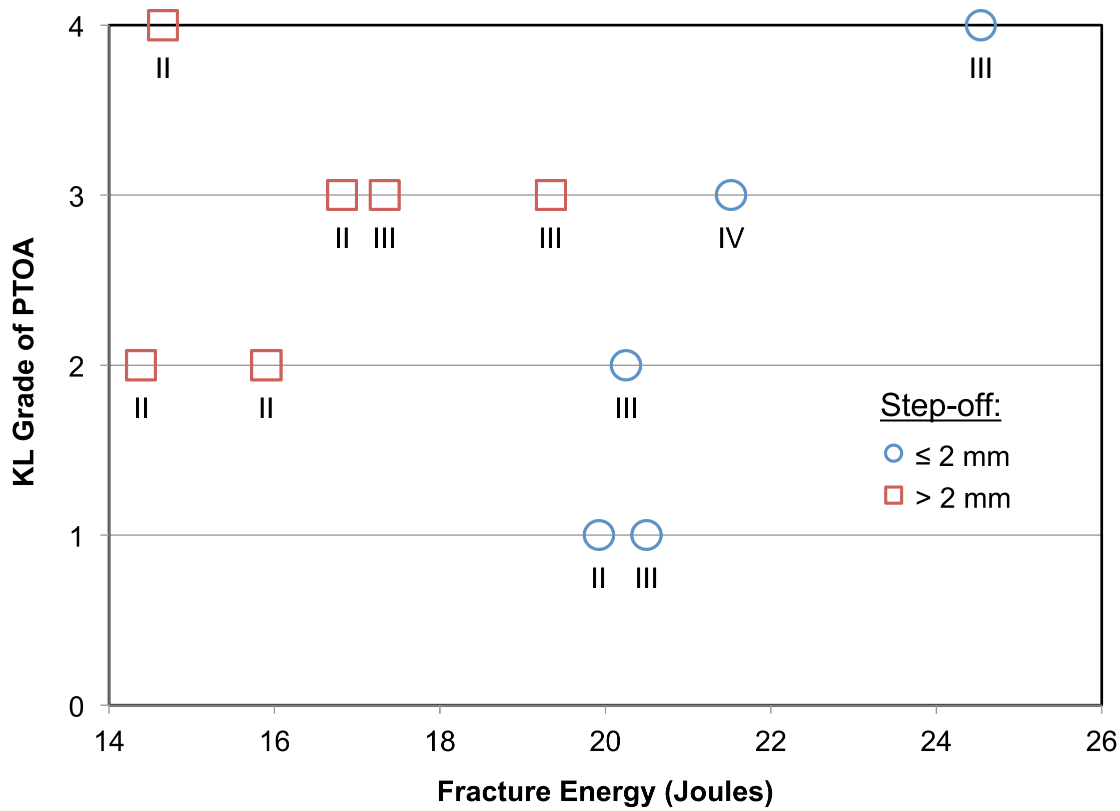

Figure 1. Fracture energy vs KL Grade. Labels below data points indicate the Sanders fracture classification.

A universally applicable, objective CT-based method for quantifying articular fracture severity

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Disclosures: None

INTRODUCTION: The assessment of injury severity is a critical step in the treatment of articular fractures. Severity assessments are used to inform clinical and surgical decision making through anticipation of patient outcomes. These assessments generally involve interpretation of radiographs or CT image data to characterize aspects of the fractures that predispose to poor prognoses. In recognition of the poor reliability of existing clinical severity assessments, new objective severity metrics have been developed that are firmly rooted in mechanics and provide capable alternatives for use in research, where reliable data are paramount. One of these metrics, fracture energy, has previously been relegated to use in a single joint. In an effort to expand the clinical utility of fracture energy as an objective metric of severity, we have developed new methods to implement fracture energy as a universal tool in any fracture with pre-operatively available CT-scans.

METHODS: An existing, objective, CT-based method for determining the energy expended in a bone fracture was extended to enable its use in more fracture types. The new methodology requires only a pre-operative CT-scan of the fractured joint. The CT images are then segmented, identifying all bone fragments to generate a 3D model of the fracture. Surfaces are then smoothed in Geomagic Design X (3DS Systems, Rock Hill, SC) to remove voxellation effects and to prepare the data for use in a surface classification algorithm. An automated classifier then identifies fractured surfaces on the fragments, with a graph cut method used to create a clear boundary between the intact and fractured bone surfaces. Manual adjustment of this boundary is performed to finalize the fractured surface identification. The CT Hounsfield Unit intensities are then sampled along the fractured surface for use in obtaining a bone density distribution over the surface. The fractured areas are then scaled by these location specific densities and multiplied by a density dependent energy release rate to obtain the fracture energy. Articular comminution can be quantified by measuring the fracture edge length along the articular surface from the fractured surface boundaries. The new methodology was validated by comparing the fracture energies obtained for a series of 20 pilon fractures which had previously been assessed using the existing methods.

RESULTS: The fracture energies computed using the new assessment methodology were compared to those computed using the prior method for validation purposes. Twenty tibial pilon fracture cases previously analyzed were evaluated using the new methodology. A Bland-Altman plot comparing the results is shown in Figure 1. There was strong agreement between the previous fracture energy evaluation method and the expanded methodology with all but one case lying within the confidence interval. On average, there was a bias that the prior methodology measured around 1.5J higher than the present method; based upon these cases, the data suggest that 95% of measurements with the new methodology will be within 3-5J of those made using the prior methodology.

DISCUSSION: Fracture energy is a proven metric capable of objectively analyzing fracture severity over a continuous spectrum of severity. Previous methodologies were limited by their requirement of intact contralateral scans and joint specific parameters. The new methodology has more flexibility as it only requires a CT-scan containing the fractured region and can be readily retrained to classify fractured areas in any joint. The simple articular comminution metric is also readily applicable to any articular fracture (see Figure 2 for the evaluation of a tibial plateau fracture). The articular fracture edges are readily identified in any joint and have physiological meaning, as chondrocyte death is known to be elevated along fracture edges.

SIGNIFICANCE: The methods for assessing fracture energy described are highly useful for stratifying severity over a continuous range. It has the potential to be an important tool for both clinical and research applications within orthopaedics.

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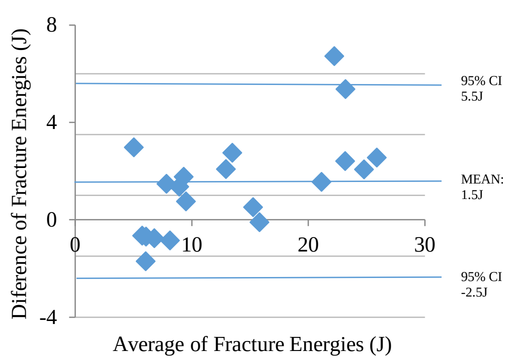

Figure 1. Bland-Altman plot comparing fracture energies obtained from the original and the newly expanded methodologies.

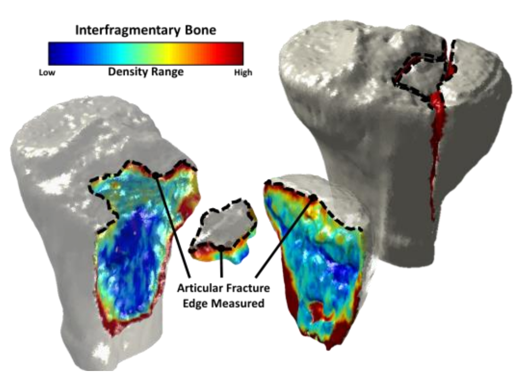

Figure 2. Fracture-liberated surface area and bone densities shown across an exploded view of a tibial plateau fracture. The dashed lines indicate where the articular comminution measure is obtained from.

Objective Prediction of Post-Traumatic OA Risk Following Acetabular Fractures Based on Severity

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Disclosures: None

INTRODUCTION: Post-traumatic osteoarthritis (PTOA) is a debilitating condition that presents following trauma to an articular joint. Despite advances in reduction and fixation strategies over the past two decades, there remains a significant prevalence of PTOA in patients that suffer acetabular fractures. Up to 25% of patients develop PTOA after surgical reduction and fixation [1]. Current approaches to treatment are largely based on clinical intuition and accumulated experience. They are subjective in nature and do not adequately improve patient outcomes or reduce PTOA risk. Recent studies have demonstrated the utility of fracture energy and articular comminution as objective measures of fracture severity for use in predicting PTOA risk [2-4]. The goal of the present study is to determine if PTOA risk following acetabular fractures can be predicted based on objective measures of severity.

METHODS: Seventeen patients with surgically reconstructed acetabular fractures were consented for this IRB approved study. Patients were selected from a larger series of 263 acetabular fractures based on having pre-operative CT scans available with a minimum 24-month follow-up. Fracture energy and articular comminution, were measured from preoperative CT scans using previously established objective CT-based methods [4]. Bone fracture fragments were segmented from CT scans to generate 3D models of the fractured pelves. Interfragmentary surface areas were then identified on the fragments using a surface classification algorithm. Location-specific bone densities (Figure 1) were then used to appropriately scale interfragmentary surface areas by density-dependent energy release rates to obtain the fracture energy. An additional measure reflecting the amount of articular comminution was derived by quantifying the articular fracture edge length, defined as the length of the edge at the intersection between interfragmentary and subchondral bone surfaces. Outcomes were evaluated using KL grading of radiographs taken at least 24 months post-injury.

RESULTS: Fracture energies for the 17 acetabular fracture cases ranged from 4.6 to 32.8J with a mean±SD of 17.6±8.6J, and the articular fracture edge length ranged from 39.4 to 364.8mm with a mean±SD of 197.4±91.1mm. Twelve of the patients developed PTOA (KL≥2) in their hip following treatment. All but one of the cases with fracture energy exceeding 15J experienced some arthritic changes (Figure 2). There did not appear to be any strong correlations between fracture energy and articular comminution with KL grading.

DISCUSSION: Fractures of the acetabulum are generally considered severe and warrant thorough examination of treatment options. The present data suggest a damage threshold for fracture energy around 15J, above which patients can be expected to experience PTOA. This preliminary investigation into preoperative prediction of PTOA risk did not demonstrate a statistically significant correlation between objective measures of severity and patient outcomes. However, the quality of surgical reduction is another major contributor to patient outcomes that was not yet controlled for in this study. This may explain the lack of linear correlation and is the subject of ongoing investigation.

SIGNIFICANCE: The results of this study suggest the possibility of a severity threshold above which fractures predictably progress to PTOA in spite of surgical management. Objective CT-based severity metrics combined with present clinical knowledge may offer advantages in understanding fractures of the acetabulum.

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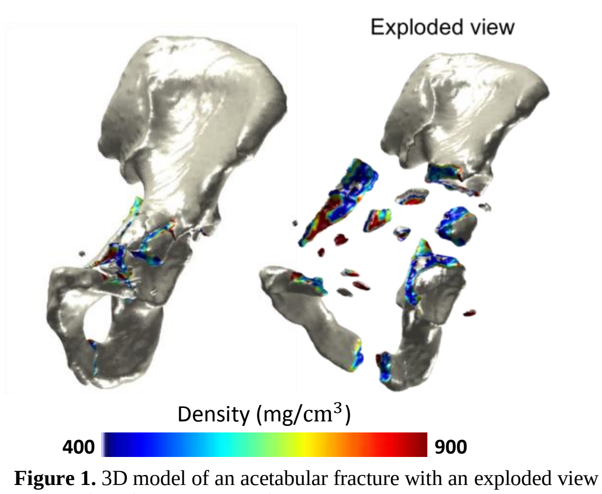

Figure 1. 3D model of an acetabular fracture with an exploded view (right) of the fragments. Interfragmentary bone is colored according to its density distribution.

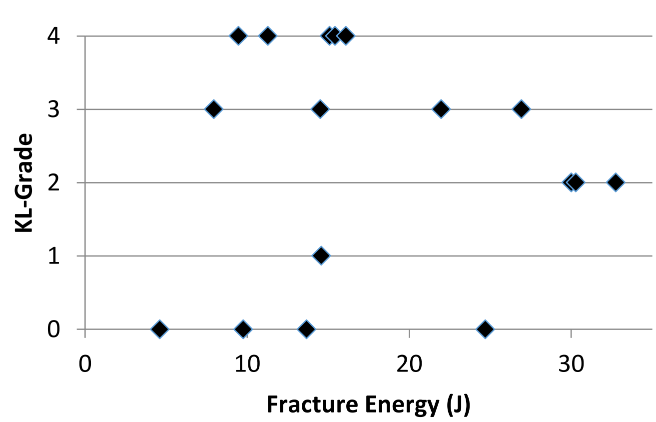

Figure 2. KL-Grade of PTOA vs. Fracture Energy.

Fracture Severity Predicts OA Risk Following Intra-Articular Fractures

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Purpose:

Surgeons currently treat displaced intra-articular fractures (IAFs) by reducing and stabilizing the articular fragments, but even in the best of hands, an IAF frequently leads to disabling post-traumatic osteoarthritis (PTOA) within two to five years. This is true across a variety of articular joints, including those of the ankle, hindfoot, and hip. IAFs are particularly devastating injuries. When PTOA develops, it brings substantial pain, disability, lost work capacity, and decreased general health status. Recent advances in objective IAF severity assessment have provided unprecedented opportunities to study the relationship between fracture severity and PTOA risk. The purpose of this study was to test the hypothesis that the severity of an IAF, independent of the joint it involves, can be used as a predictor of PTOA risk.

Methods:

Sixty-one patients presenting with IAFs of their acetabulum (n=17), calcaneus (n=13), or distal tibia (n=31) were consented for retrospective study. Patients were selected from a larger series based on availability of pre-operative CT scans and a minimum of 20 months' radiographic follow-up. Objective assessment of fracture severity involved measuring the fracture energy and the degree of articular involvement from pre-operative CT scans using previously established methods (Figure 1). The amount of the articular surface involved in the fracture was defined as the length of the fracture edge at the joint surface, a parameter chosen based on prior in vitro work establishing a high degree of chondrocyte death along fracture edges. This measure was normalized to account for variation in the amount of articular surface between different joints. Outcomes were evaluated using KL grading of radiographs taken at least 20-months post-injury, and PTOA status was defined as a KL grade ≥ 2. Descriptive statistics were completed, and the relationship between IAF severity (defined as fracture energy or articular fracture length) and PTOA development was modeled using logistic regression.

Results:

Fracture energies for the 61 fractures ranged from 3.6 to 32.8J with a mean ± SD of 16.4 ± 6.8J, and the articular fracture edge lengths ranged from 35.8 to 364.8mm with a mean ± SD of 146.0 ± 78.1mm. Thirty-five fractured joints (57% of those studied) had developed PTOA (KL≥2) at their longest follow-up. Both fracture energy ($p<0.001$; Figure 2), and scaled articular fracture edge length ($p<0.01$) were found to be strongly predictive of PTOA risk (Table 1).

Conclusions:

The results of this study demonstrate a strong association between fracture severity and PTOA risk, despite surgical management partly aimed at avoiding PTOA. Relationships between the severity of the fracture, the difficulty of surgical management, and the quality of the surgical result have not yet been controlled for in this study. Combining objective CT-based metrics with present clinical knowledge may offer advantages in understanding fractures of articulating joints that are useful in guiding treatment to decrease the likelihood of PTOA after an IAF.

Acknowledgements:

Supported by the National Institute of Arthritis and Musculoskeletal and Skin Diseases of the National Institutes of Health under award numbers P50AR055533 and R21AR061808. This work was also supported by the Assistant Secretary of Defense for Health Affairs through the Peer Reviewed Medical Research Program under Award No. W81XWH-15-2-0087. The content is solely the responsibility of

the authors and does not necessarily represent the official views of the National Institutes of Health or the Department of Defense.

Table 1. Relationship Between Intra-Articular Fracture Severity and PTOA

	Coefficient Estimate	SE	p-value	OR	95%CI
Fracture Energy	0.18	0.05	0.001	1.20	1.08-1.33
Scaled Articular Fracture Edge Length	0.04	0.01	0.009	1.04	1.01-1.07

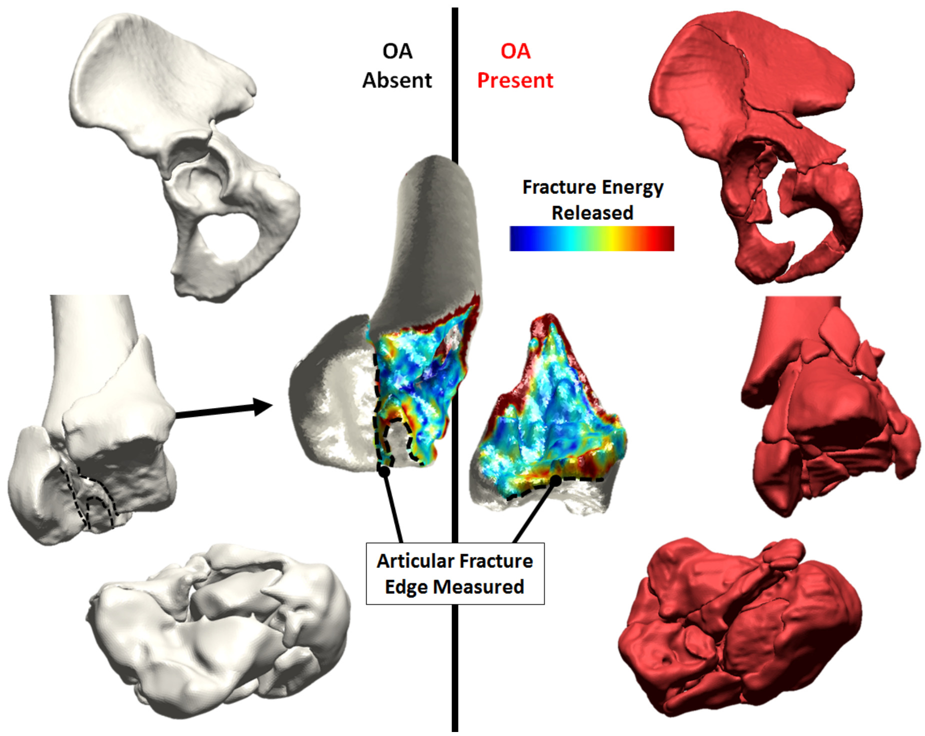

Figure 1. Objective Severity Assessment for Intra-Articular Fractures

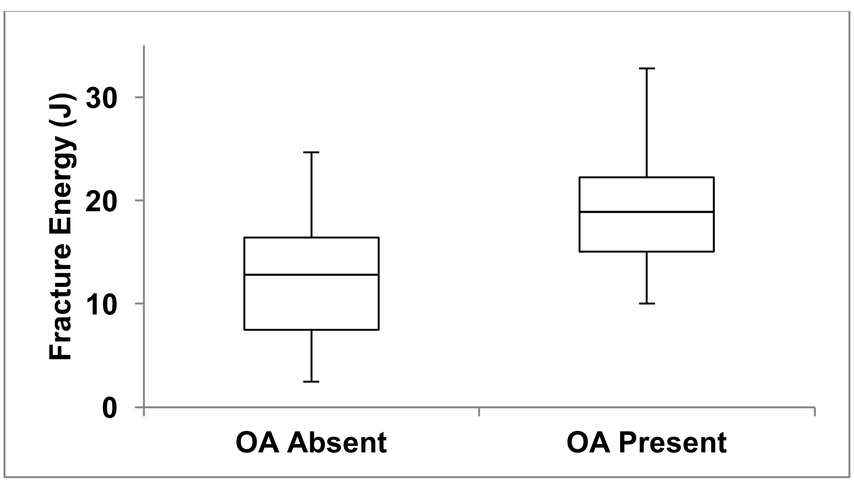

Figure 2. Fracture Energy and PTOA

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W81XWH-15-2-0087:

Pathomechanics of Post-Traumatic OA Development in the Military Following Articular Fracture

Principal Investigator: Donald D. Anderson, PhD

30 September 2015 – 29 September 2018 (POP)

Total Award Amount: $755,257

1

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Military relevant issue to be solved

- Military health care providers lack knowledge needed to adequately counsel patients on expected outcomes following combat-related intra-articular fractures (IAFs) and the likelihood of PTOA.
- This project is studying outcomes following combat-related IAFs and using CT-based metrics of influential mechanical factors to develop PTOA risk prediction models.
- This research: (1) expands upon prior work to develop objective predictors of PTOA risk; (2) tests whether the novel CT-based assessments originating from the civilian population are equally valuable in the military; and (3) lays the foundation for a platform incorporating assessment of fracture severity and contact stress as a central piece of clinical care and in future clinical trials.

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Project Funding

Current Budget	Expended Funds	%
$755,257	$289,632	38%

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Statement of Work

Specific Aim 1:	Evaluate pre- and post-treatment CT data from patients with combat-related IAFs to measure fracture severity and post-reduction contact stress exposure
Major Task 1: Regulatory Approval	
Subtask 1.1: Obtain local IRB	
Subtask 1.2: Obtain HRPO approval	
Milestone #1: Regulatory approval received	
Major Task 2: Adapt CT Analysis Methods	
Subtask 2.1: Obtain representative CT studies	
Subtask 2.2: Trial analysis methods with CT studies	
Subtask 2.3: Modify analysis methods as needed	
Milestone #2: Co-author manuscript on methods to analyze combat-related IAFs	
Major Task 3: Subject Identification	
Subtask 3.1: Obtain potential subject list with demographic and injury data from DoDTR	
Subtask 3.2: Screen available CT scans for requisite images for inclusion	
Milestone #3: Subject list finalized	
Major Task 4: CT Analyses	
Subtask 4.1: De-identified CDs compiled and express mailed from Site 2 to Site 1	
Subtask 4.2: CT calculations for injury severity and post-reduction contact stresses	
Milestone #4: Co-author manuscript on fracture severity and post-reduction contact stress measures in patients with combat-related IAFs	

Specific Aim 2:	Measure the occurrence of PTOA up to ten years following fracture reduction surgery
Major Task 5: PTOA radiographic frequency	
Subtask 5.1: Identify radiographs for KL grading; multiple investigators do KL grading grade	
Milestone #5: Co-author paper detailing PTOA incidence &grading for patients with combat-related IAFs	

Specific Aim 3:	Quantify the extent to which fracture severity and post-reduction contact stress predict PTOA
Major Task 6: PTOA symptoms and quality of life	
Subtask 6.1: Identify subjects' contact information through DoD and/or VA sources	
Subtask 6.2: Conduct prospective contacting of subjects for outcomes questionnaires	
Milestone #6: Co-author manuscript detailing symptoms and treatment timelines for patients with combat-related IAFs	
Subtask 6.3: Correlate CT-based analysis results with KL grade/PTOA status, questionnaire outcomes, and various radiographic results	
Milestone #7: Co-author manuscript detailing relationships between CT-based results and PTOA outcomes – PTOA risk model	

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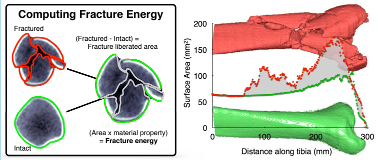
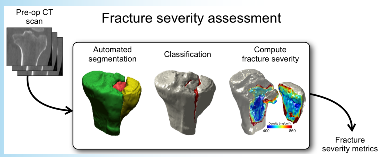
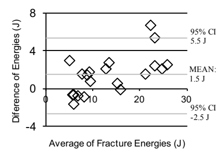
Fracture Severity Assessment

Old Method



New Method





Bland-Altman plot comparing fracture energies obtained from the old and new methods.

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Clinical Study

- Multi-center clinical study involving large and diverse group of patients, including 75 plateau and 52 plafond fractures.
- Explored the hypothesis that fracture severity metrics are higher in tibial plafond than in plateau fractures, which could explain why plafond fractures are more susceptible to PTOA than plateau fractures.
- Range of fracture energies measured for plateau fractures was 3.2-33.2J and for pilon fractures was 3.6-32.2J. The fracture energies (mean± SD) of the plateau fractures were 13.3±6.8J, and they were 14.9±7.1J for the pilon.
- No differences in fracture energies between the two fracture types, but plateau fractures did have greater involvement of the articular surface (p<0.001).
- Similar fracture energies and greater articular involvement in the tibial plateau suggest that it may be more tolerant of impact injury compared to the tibial plafond.

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PTOA Risk Prediction

- Sixty-one civilian patients presenting with IAFs of their acetabulum (n=17), calcaneus (n=13), or distal tibia (n=31) were consented for retrospective study. Tested hypothesis that the severity of an IAF, independent of the joint it involves, can predict PTOA risk.
- Patients selected based on availability of pre-op CT and a minimum of 20-month radiographic follow-up. Outcomes evaluated using KL grading of radiographs, and PTOA presence defined as KL ≥ 2. The relationship between IAF severity (defined as fracture energy or articular fracture length) and PTOA development was modeled using logistic regression.
- Fracture energies varied between joints, ranging from 3.6 to 32.8J with a mean ± SD of 16.4 ± 6.8J, and the articular fracture edge lengths ranged from 35.8 to 364.8mm with a mean ± SD of 146.0 ± 78.1mm. Thirty-five fractured joints (57% of those studied) had developed PTOA (KL≥2) at their longest follow-up. Fracture energy was strongly predictive of PTOA risk (p<0.001), a finding consistent with our prior work that only included the ankle joint.

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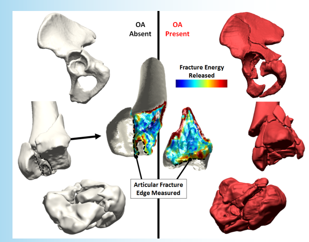
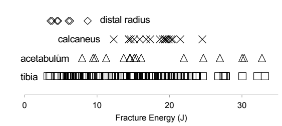
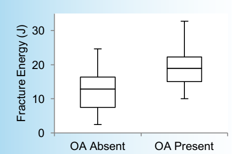
Fracture Severity and PTOA Risk



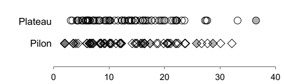
Objective severity assessment for a variety of intra-articular fractures.



Fracture energies in IAFs of the distal radius, calcaneus, acetabulum, and tibia (plateau and plafond).



Fracture energy and PTOA risk



Fracture energies for all civilian patients (open symbols) and military patients (closed symbols) plotted on the same chart show similar ranges of severity.

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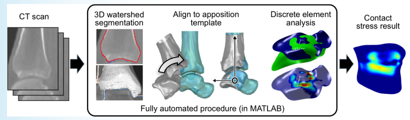
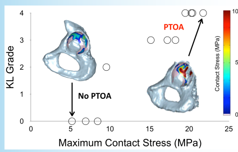
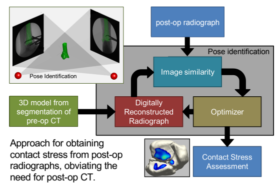
Post-Reduction Contact Stress



Schematic of fully automated procedure for determining habitual contact stress exposure in a given articular fracture reduction, with geometry extracted from CT scan data.



KL grade was highly correlated with maximum contact stress at > 24-month follow-up for these patients with IAFs of the acetabulum.



Approach for obtaining contact stress from post-op radiographs, obviating the need for post-op CT.

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Research/Development Timeline

	2015	2016				2017				2018		
	Oct-Dec	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec	Jan-Mar	Apr-Jun	Jul-Sep
Specific Aim 1: Evaluate pre- and post-treatment CT data from patients with combat-related IAFs to measure fracture severity and post-reduction contact stress exposure												
Major Task 1: Regulatory Approval												
Obtain local IRB	■											
Obtain HRPO approval	■											
Regulatory approval received	I											
Major Task 2: Adapt CT Analysis Methods												
Obtain representative CT studies		I										
Trial analysis methods with CT studies		■										
Modify analysis methods as needed		■	■									
Co-author manuscript on methods				I								
Major Task 3: Subject Identification												
Obtain potential subject list from DoDTR			I									
Screen available cases for inclusion				■	■							
Subject list finalized						I						
Major Task 4: CT Analyses												
De-identified CDs compiled and mailed				■	■	■						
CT analysis of severity and contact stress					■	■	■	■				
Co-author manuscript on fracture severity and contact stress measures									I			

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Research/Development Timeline

	2015	2016				2017				2018		
	Oct-Dec	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec	Jan-Mar	Apr-Jun	Jul-Sep
Specific Aim 2: Measure the occurrence of PTOA up to ten years following fracture reduction surgery												
Major Task 5: PTOA radiographic frequency												
Identify radiographs and do KL grading					■	■	■	■				
Co-author paper detailing PTOA incidence and grading									I			
Specific Aim 3: Quantify the extent to which fracture severity and post-reduction contact stress predict PTOA												
Major Task 6: PTOA symptoms and quality of life measures												
Identify subjects' contact information through DoD and/or VA sources					■	■						
Conduct prospective contacting of subjects for outcomes questionnaires							■	■	■	■		
Co-author manuscript detailing symptoms and treatment timelines										I		
Correlate CT-based analyses with KL grade/PTOA status and other outcomes										■	■	■
Co-author manuscript relating CT-based results and PTOA outcomes – developing PTOA risk model												I

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Challenges

- Difficulty finding cases where post-op CT was obtained. New method of analyzing post-op radiograph should help with this in the future.
- Delays in identifying and pulling cases from Walter Reed.
- Patients unavailable for follow-up.

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Defense Health Agency

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Intellectual Property / Publications Deriving from this Project

Publications, conference papers, and presentations

- Kempton L, Dibbern K, Anderson D, Morshed S, Higgins T, Marsh J, McKinley T. Objective metric of energy absorbed in tibial plateau fractures corresponds well to clinician assessment of fracture severity. J Orthop Trauma 30(10):551-6, 2016.
- Dibbern K, Kempton L, Higgins T, Morshed S, McKinley T, Marsh J, Anderson D. Fractures of the tibial plateau involve similar energies as the tibial pilon but greater articular surface involvement. J Orthop Res. 35(3):618-24, 2017.
- Kempton L, Dibbern K, Anderson D, Morshed S, Higgins T, Marsh J, McKinley T. Objective metric of energy absorbed in tibial plateau fractures corresponds well to clinician assessment of fracture severity. 31st Annual Meeting of the OTA, October 7-10, 2015, San Diego, CA.
- Dibbern K, Kempton L, Higgins T, McKinley T, Marsh J, Anderson D. Energy absorbed in fracturing is similar in tibial plateau and pilon fractures over a full spectrum of severity. 83rd Annual Meeting of the AAOS, March 1-5, 2016, Orlando, FL.
- Kempton L, Dibbern K, Anderson D, Morshed S, Higgins T, Marsh J, McKinley T. CT-based metric of tibial plateau fracture energy corresponds well to clinician assessment of fracture severity. 83rd Annual Meeting of the AAOS, March 1-5, 2016, Orlando, FL.
- Dibbern K, Kempton L, McKinley T, Higgins T, Marsh J, Anderson D. Quantifying tibial plateau fracture severity: Fracture energy agrees with clinical rank ordering. 62nd Annual Meeting of the ORS, March 5-8, 2016, Orlando, FL.
- Dibbern K, Higgins T, Kempton L, McKinley T, Marsh J, Anderson D. Objective fracture energy assessment of tibial plateau fractures loosely corresponds to Schatzker classification. 62nd Annual Meeting of the ORS, March 5-8, 2016, Orlando, FL.
- Rao K, Dibbern K, Phisitkul P, Marsh J, Anderson D. Relating fracture severity to post-traumatic osteoarthritis risk after intra-articular calcaneal fractures. 62nd Annual Meeting of the ORS, March 5-8, 2016, Orlando, FL.
- Mosqueda J, Dibbern K, Willey M, Marsh J, Anderson D. Elevated contact stress after surgical reduction of acetabular fractures correlates with progression to post-traumatic osteoarthritis. 40th Annual Meeting of the ASB, August 2-5, 2016, Raleigh, NC.
- Dibbern K, Kempton L, Higgins T, McKinley T, Marsh J, Anderson D. Clinical fractures of the tibial plateau involve similar energies as the tibial pilon. 40th Annual Meeting of the ASB, August 2-5, 2016, Raleigh, NC.
- Rao K, Dibbern K, Phisitkul P, Marsh J, Anderson D. Post-traumatic OA risk relative to intra-articular calcaneal fracture severity. 32nd Annual Meeting of the OTA, October 5-8, 2016, National Harbor, MD.
- Dibbern K, Drew A, Anderson D. A universally applicable, objective CT-based method for quantifying articular fracture severity. 63rd Annual Meeting of the ORS, March 19-22, 2017, San Diego, CA.
- Dibbern K, Willey M, Phisitkul P, Glass N, Marsh J, Anderson D. Fracture severity predicts OA risk following intra-articular fractures. 2017 OARSI World Congress on Osteoarthritis, April 27–30, 2017, Las Vegas, Nevada.

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What's Next

- Remaining hurdles to integrating methods into clinical practice need to be addressed.
- Mostly involving time and effort required to obtain measures.
- Methods identified for expediting the analyses and grants being written to fund further development.

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Objective CT-Based Assessment of Severity in Articular Fractures of the Tibial Pilon

Jessica Rivera,[1] Kevin N. Dibbern,[2] J. Lawrence Marsh,[2] Donald D. Anderson[2]
[1] San Antonio Military Medical Center, San Antonio, TX, USA
[2] The University of Iowa, Iowa City, IA

Background:

Assessing injury severity is a critical step in treating articular fractures, with important implications in clinical and surgical decision making. A primary treatment goal is often anatomical reduction of the joint surface to restore limb function and forestall post-traumatic osteoarthritis (PTOA). Fracture energy has been utilized to objectively assess fracture severity in the lower extremities and predict PTOA risk, but only in patients with isolated joint fractures. The goal of this study was to determine the utility of these same fracture severity measures in patients exposed to high energy trauma, many of whom have additional fractured joints in their extremities, with limb salvage as a treatment goal.

Methods:

Twenty military patients presenting with tibial pilon fractures resulting from explosion injuries were studied. These were the first analyzed from a larger series of patients being followed, with 15 of the 20 patients having suitable follow-up data currently available. Fracture energy and articular comminution were computed from pre-operative CT scan data. The CT scans were segmented to identify and generate 3D surface models of all bone fragments. Bone surfaces were then classified into intact and *de novo* fracture surfaces using a trained classification algorithm. Location-specific bone densities were then used to scale interfragmentary fracture surface areas by density-dependent energy release rates to obtain the fracture energy. Articular comminution was incorporated by quantifying the articular fracture edge length, defined as the length of the edge at the intersection between interfragmentary and subchondral bone surfaces. Outcomes were evaluated using Kellgren-Lawrence (KL) grading of radiographs and by the rate of successful limb salvage.

Results:

Fracture energies ranged from 1.3 to 28.7 J with a mean$\pm$SD of 11.9$\pm$8.0 J. Articular fracture edge length ranged from 18.5 to 256.1 mm with a mean$\pm$SD of 115.0$\pm$45.3 mm. Of the 15 patients with follow-up data available, 1 limb resulted in amputation secondary to soft tissue reconstructive challenges and 4 limbs were amputated due to the patients' pain and resultant activity restriction. Of the limbs that were amputated late, two had a KL grade of 3 and two had a KL grade of 4 for osteoarthritis grading of the ankle. There was a statistically significant difference in the fracture energies of the amputation and retained limb groups (17.4 J vs 6.6 J, respectively; $p=0.0059$) while articular fracture edge length differences trended towards significance (135.1 vs 105.3 mm; $p=0.056$). There were no significant differences in fracture energy or articular fracture edge length for different KL grades in this preliminary investigation.

Conclusion:

Fractures associated with blast injuries are generally considered severe and warrant thorough examination of treatment options. The present data suggest that the amount of energy involved in a fracture, as well as the articular fracture edge length, may predict painful and activity limited post traumatic arthritis. Post traumatic arthritis can be a contributing factor that compromises long term retention of reconstructed limbs. This preliminary investigation into pre-operative prediction of injury severity may offer insights into long term prognosis of such injuries.

Objective CT-Based Assessment of Severity in Articular Fractures of the Tibial Pilon

Kevin N. Dibbern,[1] Jessica Rivera,[2] J. Lawrence Marsh,[1] Donald D. Anderson[1]
[1] The University of Iowa, Iowa City, IA, USA
[2] San Antonio Military Medical Center, San Antonio, TX

Background:

Assessing injury severity is a critical step in treating articular fractures, with important implications in clinical and surgical decision making. A primary treatment goal is often anatomical reduction of the joint surface to restore limb function and forestall post-traumatic osteoarthritis (PTOA). Fracture energy has been utilized to objectively assess fracture severity in the lower extremities and predict PTOA risk, but only in civilian patients with isolated joint fractures. The goal of this study was to determine the utility of these same fracture severity measures in military patients, many of whom have additional fractured joints in their extremities, with limb salvage as a treatment goal.

Methods:

Twenty patients presenting with tibial pilon fractures resulting from blast injuries were studied. These were the first analyzed from a larger series of patients being followed, with 15 of the 20 patients having suitable follow-up data currently available. Fracture energy and articular comminution were computed from pre-operative CT scan data [1]. The CT scans were segmented to identify and generate 3D surface models of all bone fragments. Bone surfaces were then classified into intact and *de novo* fracture surfaces using a trained classification algorithm. Location-specific bone densities were then used to scale interfragmentary fracture surface areas by density-dependent energy release rates to obtain the fracture energy. Articular comminution was incorporated by quantifying the articular fracture edge length, defined as the length of the edge at the intersection between interfragmentary and subchondral bone surfaces. Outcomes were evaluated using KL grading of radiographs and by the rate of successful limb salvage.

Results:

Fracture energies ranged from 1.3 to 28.7 J with a mean$\pm$SD of 11.9$\pm$8.0 J. Articular fracture edge length ranged from 18.5 to 256.1 mm with a mean$\pm$SD of 115.0$\pm$45.3 mm. Of the 15 patients with follow-up data available, 1 limb resulted in amputation secondary to soft tissue reconstructive challenges and 4 limbs were amputated due to the patients' pain and resultant activity restriction. Of the limbs that were amputated late, two had a KL grade of 3 and two had a KL grade of 4 for osteoarthritis grading of the ankle. There was a statistically significant difference in the fracture energies of the amputation and retained limb groups (17.4 J vs 6.6 J, respectively; p=0.0059) while articular fracture edge length differences trended towards significance (135.1 vs 105.3 mm; p=0.056). There were no significant differences in fracture energy or articular fracture edge length for different KL grades in this preliminary investigation.

Conclusion:

Fractures associated with blast injuries are generally considered severe and warrant thorough examination of treatment options. The present data suggest that the amount of energy involved in a fracture, as well as the articular fracture edge length, may predict painful and activity limited post traumatic arthritis that contributes to late amputation in non-isolated military blast injuries. This preliminary investigation into pre-operative prediction of injury severity may offer insights into long term prognosis of such injuries.

References:

1. Dibbern KN et al. *J Orthop Research*, doi:10.1002/jor.23359, 2016.

Objective Assessment of Tibial Pilon Articular Fracture Severity Predictive of Secondary Amputation

Kevin N. Dibbern[1], Jessica C. Rivera[2], J Lawrence Marsh[1], Donald D. Anderson[1]
[1]University of Iowa, Iowa City, IA, [2]US Army Institute of Surgical Research, Fort Sam Houston, TX
kevin-dibbern@uiowa.edu

Disclosures: Kevin N. Dibbern (N), Jessica C. Rivera (N), J Lawrence Marsh (N), Donald D. Anderson (N)

INTRODUCTION: Surgeons treating high energy articular fracture cases face difficult treatment decisions when attempting fracture reduction. Primary treatment goals center on restoring limb function and forestalling the onset of post-traumatic arthritis (PTOA). The tibial pilon is especially susceptible to PTOA development, making anatomical reduction of the tibiotalar joint crucial to long term function. Additionally, assessing fracture severity in these cases presents a critical component in treatment, with important implications for clinical and surgical decision making. Fracture energy and articular comminution have been utilized as measures to objectively assess fracture severity in the lower extremities and predict PTOA risk, but only in civilian patients with isolated joint fractures [1]. The goal of this study was to determine the utility of these same fracture severity measures in military patients, many of whom have additional fractured joints in their extremities, with limb salvage as a treatment goal.

METHODS: Twenty patients presenting with tibial pilon fractures resulting from blast injuries were studied under IRB approval. These were the first analyzed from a larger series of patients being followed, with 15 of the 20 patients having suitable follow-up data currently available. Fracture energy and articular comminution were computed from pre-operative CT scan data [2]. The CT scans were segmented to identify and generate 3D surface models of all bone fragments. Bone surfaces were then classified into intact and *de novo* fracture surfaces using a trained classification algorithm. Location-specific bone densities were then used to scale interfragmentary fracture surface areas by density-dependent energy release rates to obtain the fracture energy. Articular comminution was incorporated by quantifying the articular fracture edge length, defined as the length of the edge at the intersection between interfragmentary and subchondral bone surfaces (Figure 1). Outcomes were evaluated using KL grading of radiographs and by the rate of successful limb salvage.

RESULTS: Fracture energies ranged from 1.3 to 28.7 J with a mean$\pm$SD of 11.9$\pm$8.0 J. Articular fracture edge length ranged from 18.5 to 256.1 mm with a mean$\pm$SD of 115.0$\pm$45.3 mm. Of the 15 patients with follow-up data available, 1 limb resulted in amputation secondary to soft tissue reconstructive challenges and 4 limbs were amputated due to the patients' pain and resultant activity restriction. Of the limbs that were amputated late, two had a KL grade of 3 and two had a KL grade of 4 for osteoarthritis grading of the ankle. There was a statistically significant difference in the fracture energies of the amputation and retained limb groups (17.4 J vs 6.6 J, respectively; p=0.0059) while articular fracture edge length differences trended towards significance (135.1 vs 105.3 mm; p=0.056). There were no significant differences in fracture energy or articular fracture edge length for different KL grades in this preliminary investigation.

DISCUSSION: Fractures associated with blast injuries are generally considered severe and warrant thorough examination of treatment options. The present data suggest that the amount of energy involved in a fracture, as well as the articular fracture edge length as a measure of articular comminution, may predict painful and activity limited post traumatic arthritis that contributes to late amputation in non-isolated military blast injuries. This preliminary investigation into pre-operative prediction of injury severity may offer insights into long term prognosis of such injuries.

SIGNIFICANCE: High energy injuries of the tibial pilon present complex treatment decisions. Objective measures of fractures severity may eventually provide pre-operative predictions of patient outcomes that can help guide initial operative management in cases where challenging decisions may exist.

REFERENCES: 1. Thomas, TP et al J Orthop Trauma, doi: 10.1097/BOT.0b013e3181d7a0aa, 2010. 2. Dibbern KN et al. J Orthop Research, doi:10.1002/jor.23359, 2016.

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FIGURES:

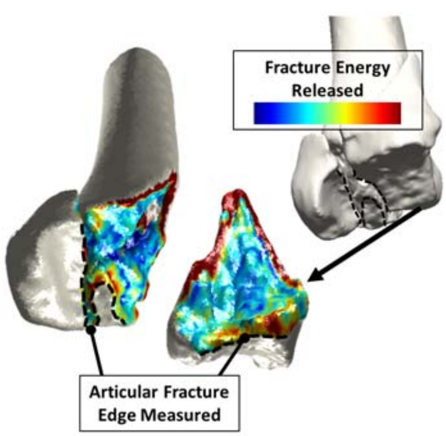

Figure 1. 3D model of a 10.1J fracture of the distal tibia with an exploded view of the fragments. The energy release rate variation across the interfragmentary surface is shown in color.

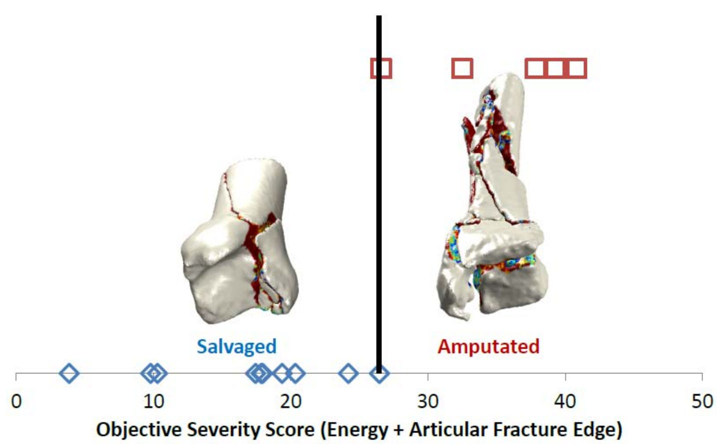

Figure 2. Objective Severity scores for 15 tibial pilon fractures. Successful salvages are shown in blue and amputations are shown in red.

Objective Metrics of Tibial Pilon Fracture Severity Predict Secondary Amputation

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INTRODUCTION: Surgeons treating patients with high energy articular fractures of the tibial pilon face difficult treatment decisions. Primary treatment goals center on restoring limb function and avoiding post-traumatic osteoarthritis (PTOA). Reliably assessing the severity of the fracture is critical in decision making. Objective metrics of fracture severity (fracture energy, articular comminution) have been shown to reflect PTOA risk, but only in civilian patients with isolated joint fractures [1]. The goal of this study was to determine the utility of these fracture severity metrics in military patients, many of whom have additional fractured joints in their extremities and have limb salvage as a treatment goal.

METHODS: Twenty patients with tibial pilon fractures due to blast injuries were studied under IRB approval. These were the first analyzed from a larger series of patients being followed, with 15 of the 20 patients having follow-up data currently available. Fracture energy and articular comminution were computed from pre-op CT scan data [2]. The CT scans were segmented to identify and generate 3D surface models of all bone fragments. Bone surfaces were then classified into intact and de novo fracture surfaces. Bone densities were then used to scale interfragmentary surface areas to obtain the fracture energy [2]. Articular comminution was quantified as the articular fracture edge length – the length of the edge at the intersection between interfragmentary and subchondral bone surfaces. Outcomes were evaluated using KL radiographic grading of OA and by the rate of successful limb salvage.

RESULTS: Fracture energies ranged from 1.3 to 28.7 J (mean±SD = 11.9±8.0 J). Articular fracture edge lengths ranged from 18.5 to 256.1 mm (115.0±45.3 mm). For 15 patients with follow-up data, 1 extremity was amputated secondary to soft tissue reconstructive challenges and 4 due to pain and activity restriction. Of the limbs amputated late, two ankles had a KL grade of 3 and two a grade of 4. There was a statistically significant difference in the fracture energies of the amputation and retained limb groups (17.4 J vs 6.6 J, respectively; $p<0.01$) while articular fracture edge length differences trended towards significance (135.1 vs 105.3 mm; $p=0.06$). There were no significant differences in fracture severity metrics for different KL grades.

DISCUSSION: Fractures associated with blast injuries are generally considered severe and warrant thorough examination of treatment options. The present data suggest that objective CT-based metrics of fracture severity could provide reliable pre-op predictions of the risk of late amputation in military blast injuries that can help guide treatment decision-making.

REFERENCES: (1) Thomas TP et al. 2010. J Orthop Trauma 24(12):764-9. (2) Dibbern KN et al. 2017. J Orthop Research 35(3):618-24.

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